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DEVELOPMENT OF A SPACE FLIGHT PROTOTYPE DOPPLER ASYMMETRIC SPATIAL HETERODYNE (DASH) SPECTROMETER FOR THE MEASUREMENT OF UPPER ATMOSPHERIC WINDS

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Final Report

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14. ABSTRACT
This report provides a summary of the progress in developing and testing a space flight prototype Doppler Asymmetric Spatial Heterodyne (DASH) interferometer, for the purposes of measuring winds in the Mesosphere and Lower Thermosphere/Ionosphere (MLTI). The motivation behind developing a prototype instrument during this SBIR Phase II is to raise the technical readiness level (TRL).

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Acknowledgments

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Dr. John Hughes and Dr. Abas Sivjee of Embry-Riddle Aeronautical University in Daytona FL and all the staff at the HAARP facility in Gakona Alaska must be acknowledged and thanked for making the two ARROW field campaigns conducted during this SBIR possible.

1. INTRODUCTION

The recent technological development of Doppler Asymmetric Spatial Heterodyning (DASH), which is an interferometric optical technique based on Spatial Heterodyne Spectroscopy (SHS) [Roesler *et al.*, 1990], allows high enough spectral resolution as to passively measure upper atmospheric Doppler winds. DASH can measure the small wavelength shifts of emission lines such as those caused by Doppler shifts from speeds typical of upper atmospheric winds and thereby measure an air parcel's line-of-sight velocity. Measuring Doppler shifts has been a historical and very successful method used for the remote sensing of Earth's upper atmospheric neutral winds. The technique of measuring Doppler shifts is not new; however, applying the optical technique of DASH to measure the Doppler shifts is.

This report outlines the recent progress made stemming from ARTEP Inc. winning an Air Force Research Laboratory (AFRL) Small Business Innovative Research (SBIR) Phase II grant to develop and test a space flight prototype DASH instrument, for the purposes of measuring winds in the Mesosphere and Lower Thermosphere/Ionosphere (MLTI). The motivation behind developing a prototype instrument is to raise the technical readiness level (TRL) of DASH with the aim of making this a future space-based operational instrument. This SBIR Phase II includes a direct laboratory measurement of a scene simulating upper atmospheric winds, validating the SBIR Phase I conceptual optical design of the DASH flight instrument which ARTEP Inc. developed.

A conceptual optical design and a conceptual mechanical design of a flight instrument have been completed in the AFRL SBIR Phase I in addition to the electrical hardware interface, estimated size, weight, power requirements, and estimated wind retrieval errors for a DASH flight instrument. The most critical component of the flight instrument is the optical design of the interferometer. The scope of the Phase II project is not sufficient to produce a full flight prototype; however, it allows for the construction of an optical train similar to what would be used for a flight instrument. The DASH interferometer is enclosed in a hermetically sealed container or enclosure, to work under vacuum and thermal conditions similar to those as would be encountered in a space environment.

The primary objective for this SBIR Phase II is to raise the technical readiness level of DASH. The TRL is currently at 4 being demonstrated as a breadboard instrument. At the end of this Phase II effort, the TRL will increase to a 6, as the interferometer will have been operated in a space-like environment.

1.1 Background

DASH instruments can achieve similar sensitivity compared to Fabry-Perot and Michelson interferometer based instruments [Englert *et al.*, 2007] which measure Doppler shifts, with reduced fabrication and alignment tolerances on the interferometer elements. This makes the DASH technology potentially smaller and lighter but also more robust. The greatest advantage over a Michelson wind interferometer is that a DASH instrument can simultaneously measure multiple emission lines, including the possibility of an on-board calibration line, thereby allowing every acquired image to be calibrated.

There are no moving parts (e.g. no scanning mirrors) as opposed to a stepped scanned Michelson wind interferometer, which reduces the technical risk on orbit. DASH can simultaneously observe a reference or calibration line while observing the field of view (FOV) without sacrificing a portion of the FOV, meaning a 100% duty cycle. Also, a DASH interferometer requires no scan time other than single scene integration, eliminating the effect of the contamination of Doppler measurements caused scene changes which scanning Michelsons are prone to.

Previous wind instruments such as WINDII [Shepherd *et al*., 1993], HRDI [Hays *et al*, 1992] and TIDI [Killeen *et al.,* 2006] have shown there is an ever increasing link between the Stratosphere and Mesosphere. Atmospheric coupling, whereby propagating atmospheric gravity waves influence the upper atmosphere and its constituents, is currently being studied and modeled; however, there is a lack of empirical data for model validation [Meriwether, 2006]. The data product of upper atmospheric winds on a global basis, from a flight DASH instrument on a satellite platform, would provide direct empirical data to improve, validate, and assimilate into existing upper atmospheric models.

TIDI is the only satellite instrument currently measuring neutral wind velocities in the upper atmosphere on a global basis. The retrieved winds from TIDI need to be heavily averaged to be of scientific value, thereby eliminating any chance of providing meteorological or real time data on the upper atmosphere. A DASH flight instrument could provide neutral wind data which could be used both for short term forecasting and real time situational awareness of the winds in the upper atmosphere, which is currently an unfilled operational data product as identified by the US Air Force.

The principle motivation behind this SBIR is achieving the TRL required for DASH to be considered a candidate for future space-based flight opportunities which ARTEP Inc. through this AFRL SBIR Phase II seeks to accomplish.

1.2 SBIR Phase II Team

The project team members for the Phase II are listed in Table 1. The team consists of Dr. D.D. Babcock as the program's principal investigator with ARTEP Inc. seasoned flight hardware personnel Ronen Feldman, Bob Moye, and John Moser. Also included are the inventors of SHS Dr. J.M. Harlander and Dr. F. Roesler. Dr. C.R. Englert who holds a joint patent on DASH with Dr. J.M. Harlander is a non-funded collaborator from the US Naval Research Laboratory in Washington DC.

Table 1: SBIR Phase II team members

Name	Project Connection	Job Description
Dr. David Babcock	Artep Employee	Research Physicist , PI
Ronen Feldman	Artep Employee	Systems Engineer
Bob Moye	Artep Employee	Mechanical Engineer
John Moser	Artep Employee	Electrical Engineer
Dr. John Harlander	Consultant	Instrument Optical Designer
Dr. Fred Roesler	Consultant	Instrument Optical Designer
Mark Barton	Consultant	Thermal Design Engineer
Dr. Chris Englert	NRL	Research Physicist

As this is an AFRL SBIR, AFRL serves as the overall program manager, with the technical point of contact (TPOC) being Dr. T. Pedersen and the contract point of contact (POC) being J. Holmes both located at Kirtland AFB.

1.3 Phase II Objectives Review

Three specific objectives were identified and included in the SBIR Phase II proposal to complete a laboratory measurement of a scene simulating upper atmospheric winds by a DASH instrument. These three objectives are listed below.

Specific Objective I:	Develop a prototype DASH instrument
Specific Objective II:	Develop an optical Doppler shift scene generator
Specific Objective III:	Measure Doppler shifted images with known velocities which correspond to realistic $O(^1D)$ 630nm airglow emission intensities and wind speeds in Earth's upper atmosphere from 100-300km.

Specific Objective I: Develop a space flight prototype DASH instrument

Specific Objective I includes;

a. Review Phase I conceptual optical design and determine optical tolerances
b. Identify a CCD detector with performance characteristics suitable to complete laboratory Doppler wind measurements
c. Complete custom design work for optical component mounting and instrument housing
d. Develop a thermally stable vacuum interferometer enclosure
e. Assemble, integrate, align, and test all components of the DASH flight prototype

Specific Objective II: Develop an optical Doppler shift scene simulator

Specific Objective II includes;

a. Identification of a suitable monochromatic emission source to simulate an airglow emission and act as a calibration source
b. Develop hardware to simulate the scene of a Doppler shifted emission line of known wavelength shift
c. Optically design an interface to match the output of the scene generator to the two FOVs of the DASH instrument

Specific Objective III: Measure the Doppler shift from a simulated scene of the Earth's Limb

Specific Objective III includes;

a. Simultaneous FOV measurements of Doppler shifted images with known velocities which correspond to realistic $O(^1D)$ airglow emission intensities and wind speeds in the upper atmosphere from 100-300km

1.4 Project Schedule

A kick-off meeting was held on 2009.06.04 where the Phase II team developed and reviewed a task list and project schedule. The schedule includes project milestones for the 24 month effort as shown in Figure 1. Although this schedule has since been updated with sub-tasks, Figure 1 serves as a general timeline for the project.

It was decided to split the project into two basic components. The first component being the design, fabrication, and assembly of a DASH instrument which was scheduled to be completed within the first fiscal year. The second component coincides with the second fiscal year which consists of testing and data analysis.

All tasks listed in Figure 1 were completed on or ahead of schedule and within budget which in reference to the previous section (Section 1.3 Phase II Objectives Review) means that all parts of Specific Objective I, Specific Objective II, and Specific Objective III have all been successfully completed.

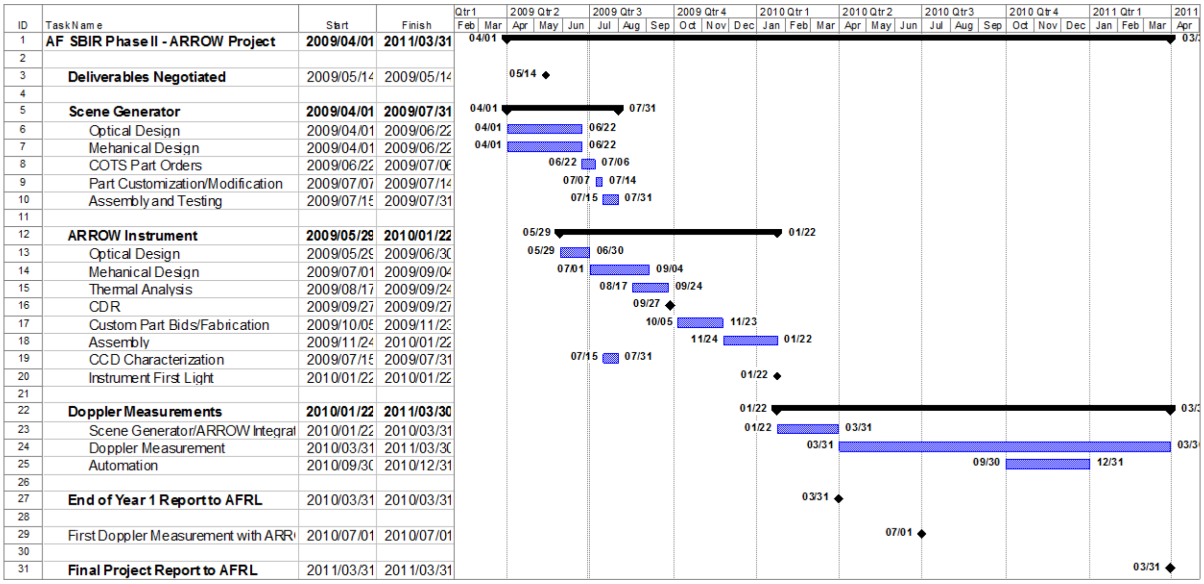


Figure 1: SBIR phase II project schedule

2. ARROW INSTRUMENT DESIGN

The DASH instrument developed during this Phase II project has been named by the science team as the Atmospheric Redline inteRferometer for dOppler Winds (ARROW).

2.1 Optical Design

It was decided after discussions between ARTEP Inc. and AFRL that a change from the Phase II proposal, including a redesign of the optical train of the lab demonstration instrument in Phase II, would be done to accommodate the potential use of the ARROW instrument from the ground. Figure 2 depicts the change in instrument schematic from the Phase I conceptual flight design to the Phase II design which has been built.

The Phase I conceptual flight design, although ideal as a flight instrument on a satellite platform, would not have been useful after this SBIR Phase II lab demonstration. The Phase II design serves to increase the TRL of DASH as the interferometer (the mission critical component) operates in a space-like environment, under vacuum.

Phase I Conceptual Flight Design   Phase II Lab Instrument Design

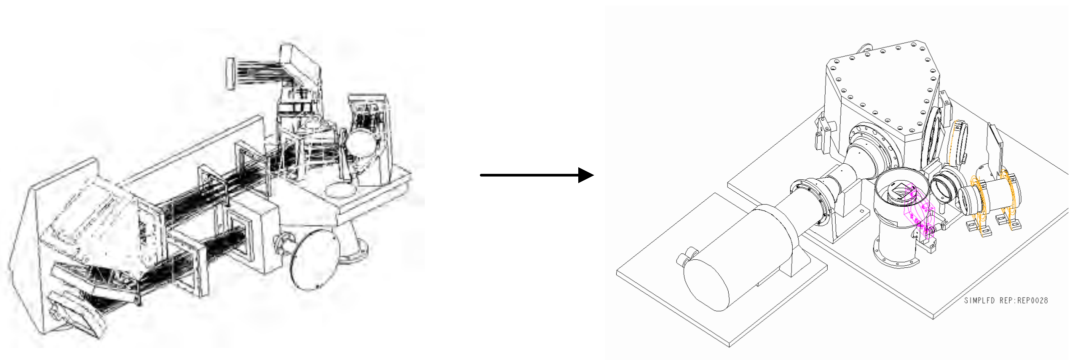


Figure 2: Schematic changes from the Phase I conceptual flight design to the ARROW instrument designed in Phase II

Below are the details of the ARROW optical design for which complete IGES files developed in ProE can be made available to AFRL on request. The ARROW optical system is shown in Figure 3.

The primary difference between the Phase I and Phase II optical designs is what the optical systems image. The Phase I optical design was developed to image the Earth's limb, which in effect images objects at infinity, whereas the Phase II optical design images an entrance aperture (A1 in Figure 3). Imaging the entrance aperture was required to allow the ARROW instrument is to potentially be used in an attempt to measure upper atmospheric winds from the ground.

The instrument optical train consists of the following components referenced to the symbols in Figure 3;

Elements along an axis perpendicular to Figure 3.

A1: rectangular aperture 27.65 x 27.65 mm square
L1: Lens 1 Edmund optics catalog NT49-286-INK 50 mm dia., 200 mm fl achromat
M1: Fold mirror Edmund optics catalog NT31-425 4-6 wave front surface mirror 38 mm x 51 mm x 3 mm thick

Elements along an axis in the plane of Figure 3.

P: Beam splitter (plate tilted 15 degrees w/r/to optical axis) Newport 20Q20NC.1
L2: Lens 2 Edmund optics catalog NT49-286-INK 50 mm dia, 200 mm fl achromat
IF: Barr interference filter ~2" diameter
I: Input aperture 33 mm diameter stop with an adjustable iris
M2: Fold mirror Edmund optics catalog NT48-452 4-6 wave front surface mirror 75 x 75 mm x 3 mm thick

L3: Collimator lens Edmund optics catalog NT45-417, 75 mm diameter, 200 mm focal length
W1: 19 mm thick 100 mm diameter vacuum cell windows
W2: Same as W1

It should be noted that the optical model shown in Figure 3.excludes the calibration lamp optics.

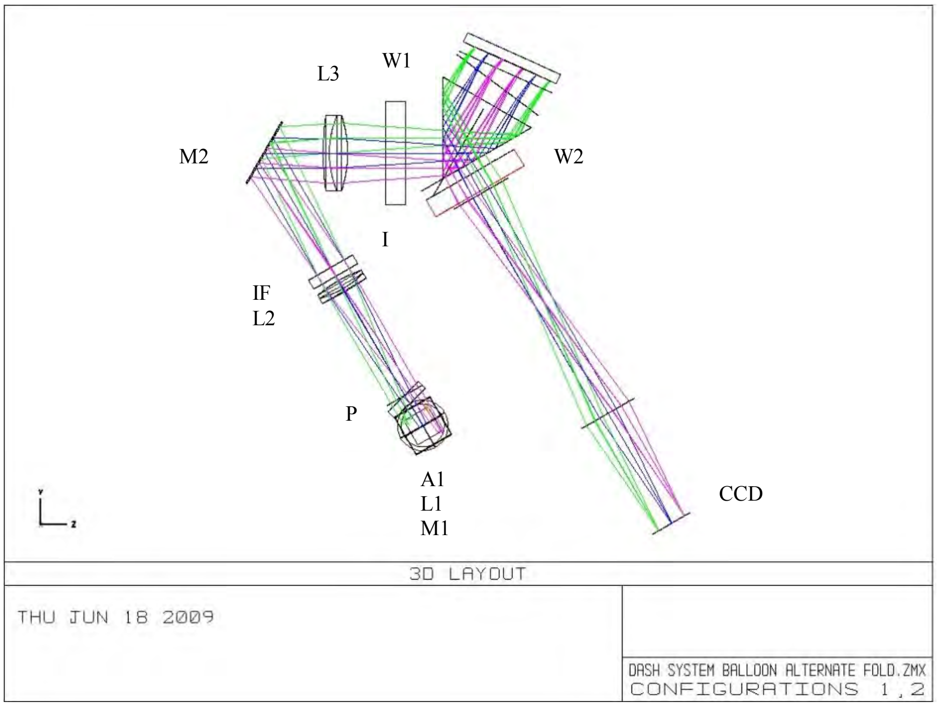


Figure 3: The ARROW instrument's optical design done with ZEMAX

The exit optics were designed and built through a subcontract with Coastal Optical Systems. The configuration shown in Figure 3 indicates the proper position of the CCD and magnification. The lenses in the exit optics are not in the proper positions, but serve to allow the raytrace to show the proper placement of the image plane on the CCD.

Mechanical adjustments to allow for optical and machining tolerance deviations are:

- Tilt mechanism for interference filter
- Tilt adjust for beam sampler (P above) 15 degrees nominal
- Tilt adjustments for mirrors
- Focus adjust for L3, (distance between I and L3)

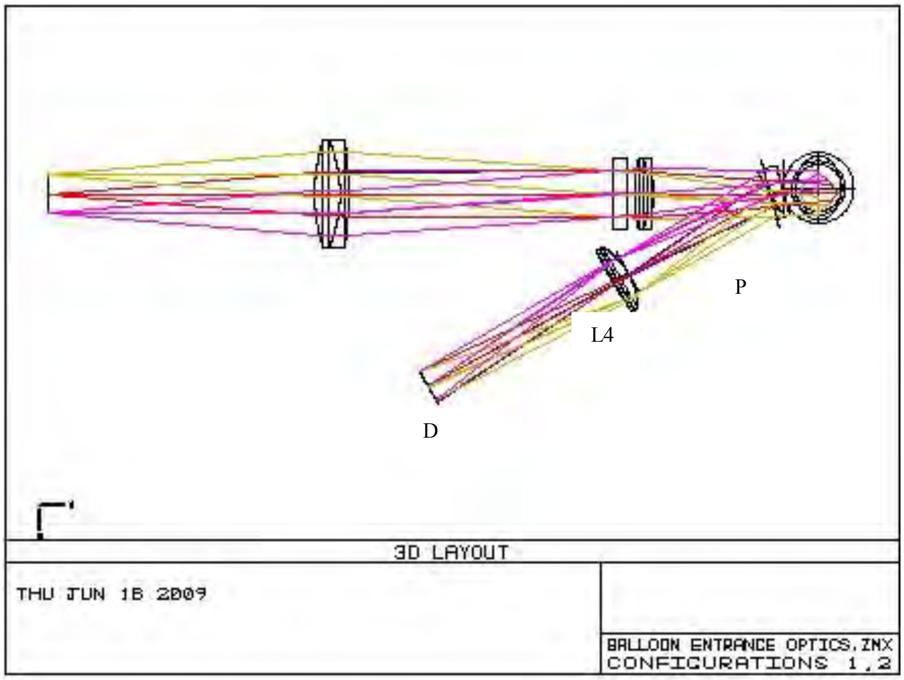


Figure 4: ZEMAX optical ray trace of the calibration lamp channel folded into the entrance optics assembly by the beam splitter P

In Figure 4, the optical axis of the calibration source was made to be in the same plane as the entrance optics - the orientation is plotted at an angle to prevent confusion in reading the raytrace.

The additional optical elements in the calibration channel are:

L4: Edmund optics NT48-246 INK 50 mm diameter, 100 mm focal length

D: Edmund optics NT54-495 holographic diffuser, 50 mm diameter, just in front (P side) of L4

Also the beam pattern onto L4 is not accurate in the above Figure 4. A quartz fiber 1/4" fiber bundle has been placed at the focal point of L4 which is 93 mm long the axis to the left of L4.

To summarize, the optical design has changed somewhat from was outlined in the Phase II proposal. Modifications have been made to the optical system to allow the ARROW instrument to be potentially used as either a ground based or balloon based instrument after laboratory testing is completed. The primary difference between the current optical design and the Phase II optical design is the shape of the field of view and the location of the imaging plane in the entrance optics.

The shape of the FOV has changed from what would be optimal for a limb imaging system, such as that which would be in orbit viewing a thermospheric airglow layer, to one that is square and now optimized for looking through an airglow layer from the ground.

2.2 Mechanical Design

2.2.1 Preliminary Design Review

The ARROW team convened and completed a preliminary design review (PDR) of the ARROW instrument on 2009.09.13. The PDR first reviewed the conceptual flight design completed in the Phase I of this SBIR. It was decided that a change from the Phase II proposal, including a redesign of the optical train of the lab demonstration instrument in Phase II, would be done to accommodate the potential use of the ARROW instrument from the ground. The Phase I design, although ideal for as a flight instrument on a satellite platform, would not have been useful after the lab demonstration.

This redesign changed the instrument's optical design, along with the mechanical layout which had to be redesigned. It should be noted that although the design of the Phase II instrument which will be built has changed from what was proposed in Phase I to allow for potential future use, the Phase I conceptual flight design is still the design for a space flight instrument.

The PDR consisted of a full review design of all mechanical components including optical holders, instrument enclosure/structure, and interferometer housing, interferometer housing thermal design, and internal environmental control.

The PDR team consisted of the full Phase II team;

Dave Babcock
Bob Moye
Layne Marlin
Fred Roesler (via telecon)
Chris Englert
John Moser
Ronen Feldman
John Harlander

The only concerns raised during the PDR were the extent of and placement of an active temperature control system that might be necessary to maintain the most stable interferometer temperature. It was decided that the final decision on thermal management would be completed during the CDR.

The PDR file used by the ARROW team to evaluate the proposed design, although not part of this report, was sent to Lt. T. Mills at Hanscom AFB as part of a private communication and is available on request.

2.2.2 Critical Design Review

The ARROW team, in addition to two external reviewers, convened on 2009.09.13 to go through a critical design review (CDR) of the ARROW instrument. The two external reviewers, Clarence Korendyke and Charlie Brown, are both NRL employees who have extensive space flight and optical hardware experience.

The CDR team reviewed all mechanical components including optical holders, instrument enclosure/structure, and interferometer housing, interferometer housing thermal design, and internal environmental control, as was done in the PDR. Three areas of concern were raised and addressed during the CDR. The three concerns were,

i). The possibility of the reference line mechanical housing interfering with the main optical beam from the entrance aperture potentially causing vignetting as shown in Figure 5. The optical path of the instrument is shown in blue with the potential vignetting caused by the reference line mechanical housing shown in the red circle.

Solution: Rotate the reference line housing to provide greater clearance between it and the L2, red-line filter, and iris assembly.

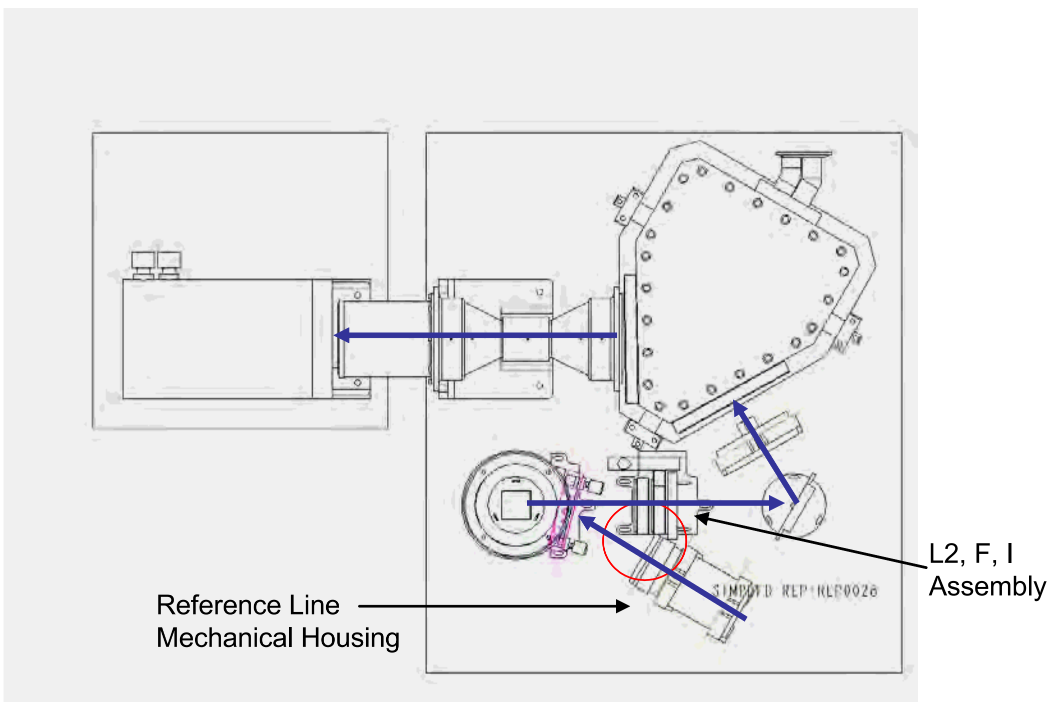


Figure 5: Potential vignetting found during CDR

ii). The thermal stability of the interferometer.

Approach: Rely on thermally isolating the interferometer well enough that passive thermal control (outlined in Section V. of this report) would be adequate to prevent fast changes in the interferometer's temperature. Add heaters and temperature control feedback loop to maintain a stable operating air temperature inside the instrument if required.

iii). The thermal expansion of the baseplate and the alignment of the output beam from the interferometer to the CCD, as any lateral shift during an exposure would be seen as a phase shift in the recorded DASH fringes. The fringe phase shift caused by a shift in the camera position due the thermal expansion of the base plate would be non-differentiable from a true Doppler shift.

Approach: The calibration (or previously referred to reference line) line should provide the capability of tracking any mechanical drifts.

The mechanical design was completed after having an optical system design to build around. The mechanical design allowed for adjustments along the optical axis to provide for fine tuning of the optical focus, but constrained optical elements laterally to facilitate rapid assembly. The final version of the ARROW instrument's mechanical design, which has been fabricated, is shown in Figure 6.

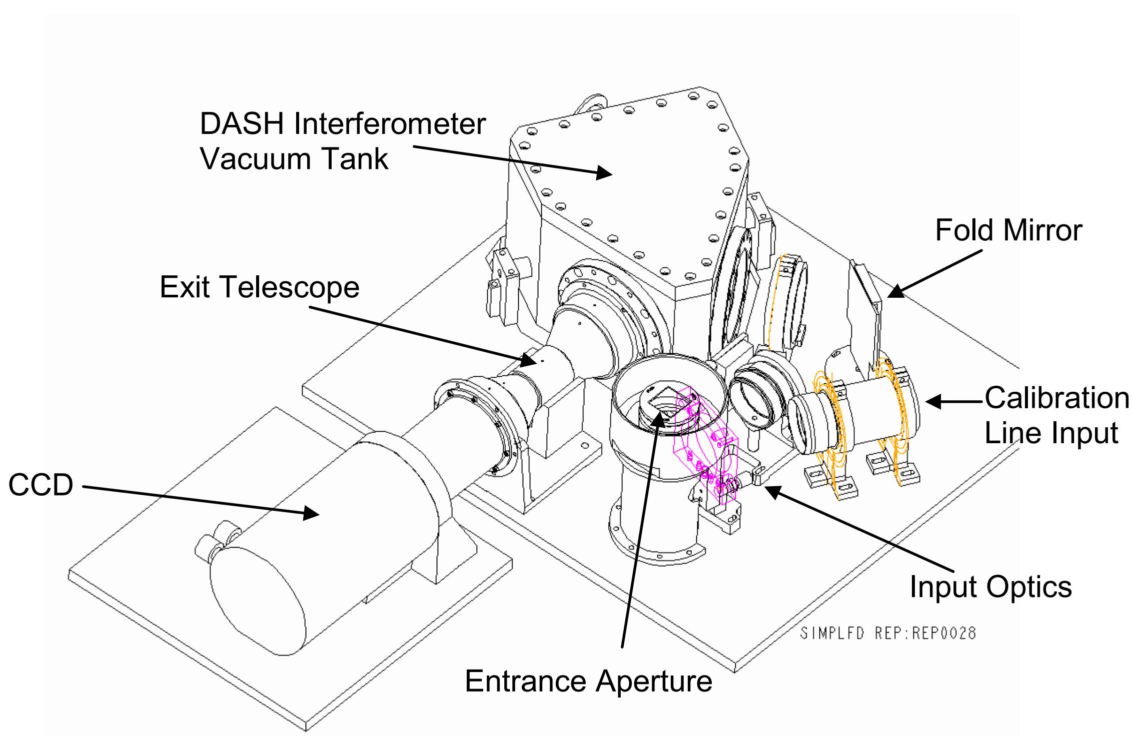


Figure 6: Schematic of the ARROW instrument's layout

Having all components mounted on two base plates, a commercial off-the-shelf (COTS) solution was chosen to provide the instrument's enclosure housing. An IMS/AMCO structural framing system was used based on 1.5" extruded aluminum tubing. This decision allowed for an economical and rigid enclosure, which is shown in Figure 7.

To make the enclosure light tight, custom aluminum panels were designed to be mounted to the extruded aluminum tubing. Figure 8 depicts the ARROW instrument with the light-tight panels attached and Figure 9 provides the final physical dimensions of the instrument.

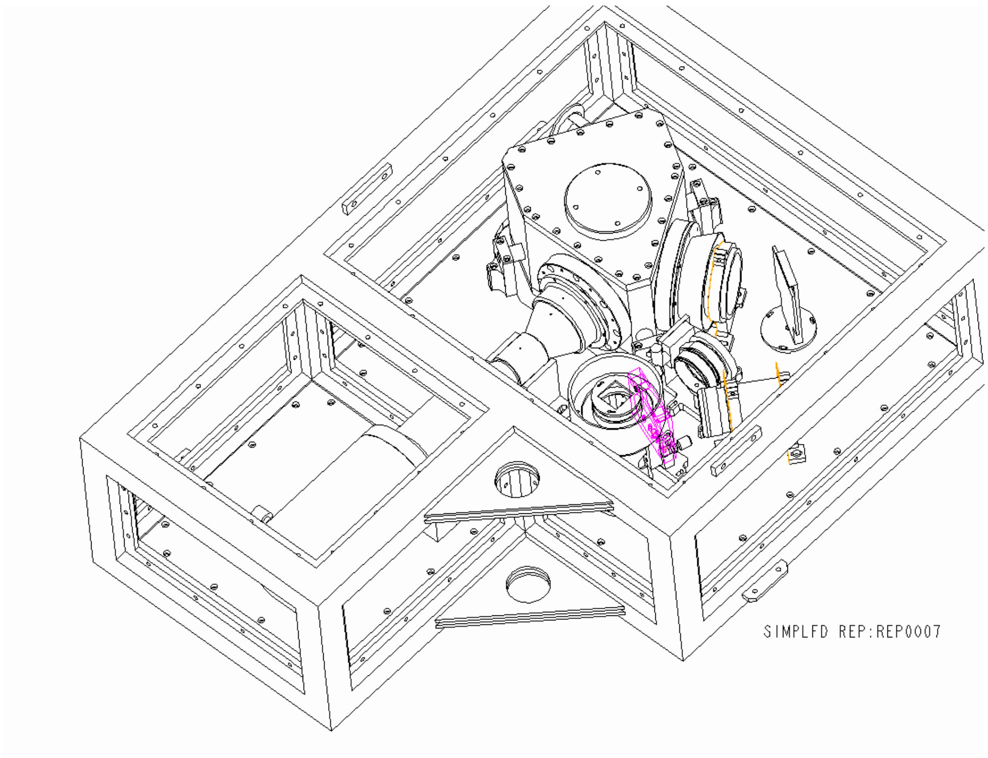


Figure 7: Schematic of the ARROW instrument with the light-tight panels off

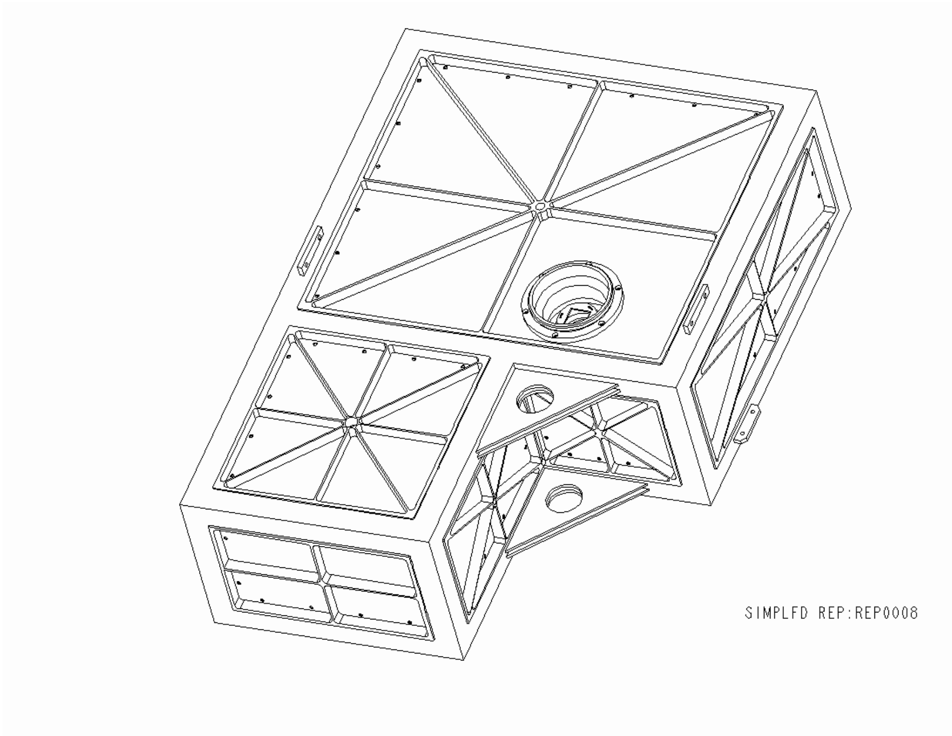


Figure 8: ARROW instrument with light-tight panels attached and visible entrance aperture seen as the top circular port

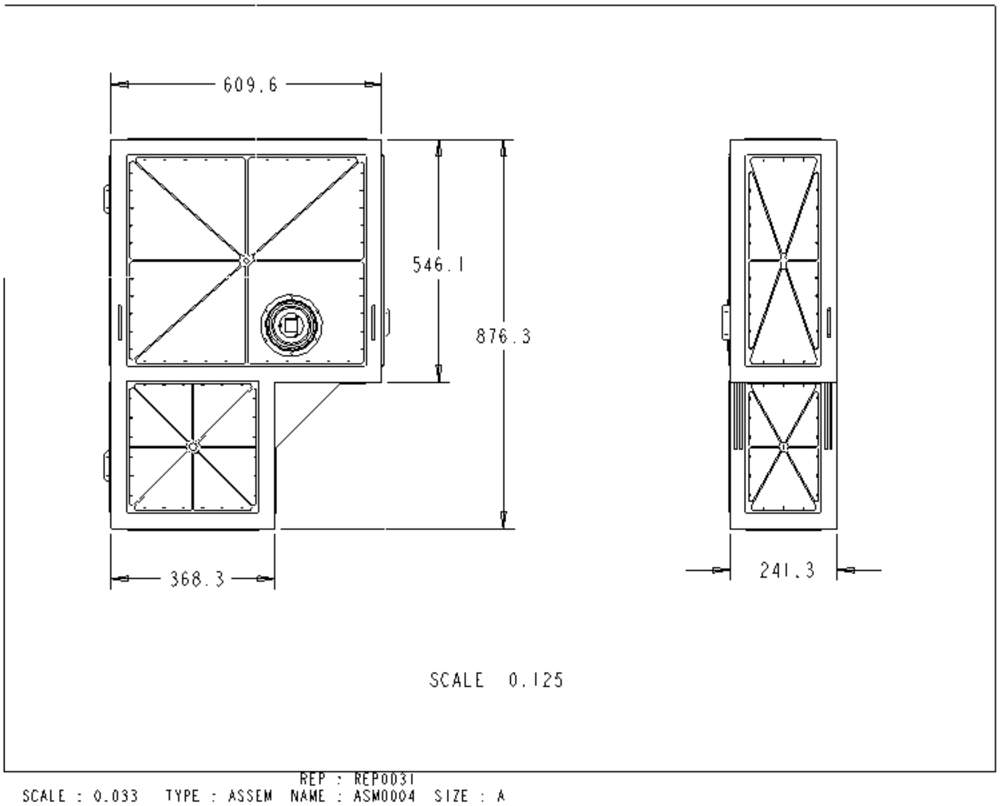


Figure 9: Physical dimensions of the ARROW instrument

Note that Figure 9 is not to 0.125 scale as indicated in the Figure and that all dimensions are listed in millimeters.

2.3 Interferometer Enclosure Thermal Design

The thermal design of the interferometer tank was been completed with a substantial effort put towards developing a design which is both passive and the most thermally stable operating in the ambient condition of a laboratory environment. After testing the interferometer performance within the enclosure where active heating was controlled to 0.1K, the interferometer was thermally stable to a few mK. This temperature stability equals a 0.01 radian/hr or ~10 m/s/hr drift in Doppler velocity – which due to the nature of a DASH interferometer accepting multiple emission line inputs, can be corrected for if a calibration line is referenced during a Doppler measurement.

The thermal design considered the following with associated mitigation strategies;

- Interferometer is a BK7 glass block
  - BK7 has a high emissivity and a high transmissivity which means it is easily affected thermally by any gradients within the enclosure

- Enclosure is thermally passive
  - This allowed us to implement some very simple and straightforward thermal control schemes

- Interferometer temperature stability

  Controlling the interferometer lent itself to the following approach;

  1. Isolate the Housing from the environment as much as possible
     - For lab testing, this will involve a foam thermal blanket on the outside of the Housing
     - For flight, this will involve an MLI (Multi-Layer Insulation) blanket
     - Same approach used through all program phases
  2. Minimize environmental stimulation directly on the interferometer through the portholes by adding porthole baffles. These would be incorporated into a flight design; however, for lab use these were manufactured but not installed.
  3. Minimize Thermal interaction between the Housing and the Interferometer
     - There is no air in the enclosure so convection is not a concern
     - Minimize radiative coupling via a low emissivity coating
  4. Create a preferential thermal path (a "thermal gate") from which to directly control temperature of the interferometer
     - Couple the Interferometer and the contact plate conductively. The temperature of the control plate was actively controlled but thermally separated from the enclosure.
     - This did not need to be a "highly" conductive connection, since steps 1-3 will reduce the current environmental parasitics by a large degree

To isolate or minimize the thermal interaction between the interferometer tank or 'housing' from the environment inside of the instrument the following was done;

- Use of a foam "thermal blanket"
- Foam is 0.5" thick to provide a good heat transfer barrier
  - Foam is low density to minimize conduction through the blanket
  - Standard blanket template foam was used
- Blanket was wrapped to avoid particulate shedding near the enclosure, additionally overwrap is electrically conductive to allow bleedoff of any accumulated static electricity near the Housing
  - 2 mil Double Aluminized Kapton Film was used for durability (tear-resistance) as well as electrical conductivity on the Inner and Outer faces of the foam blanket

– All Blanket Edges were closed out with an electrically conductive tape (such as Germanium Kapton with conductive adhesive) to avoid static buildup along edge locations

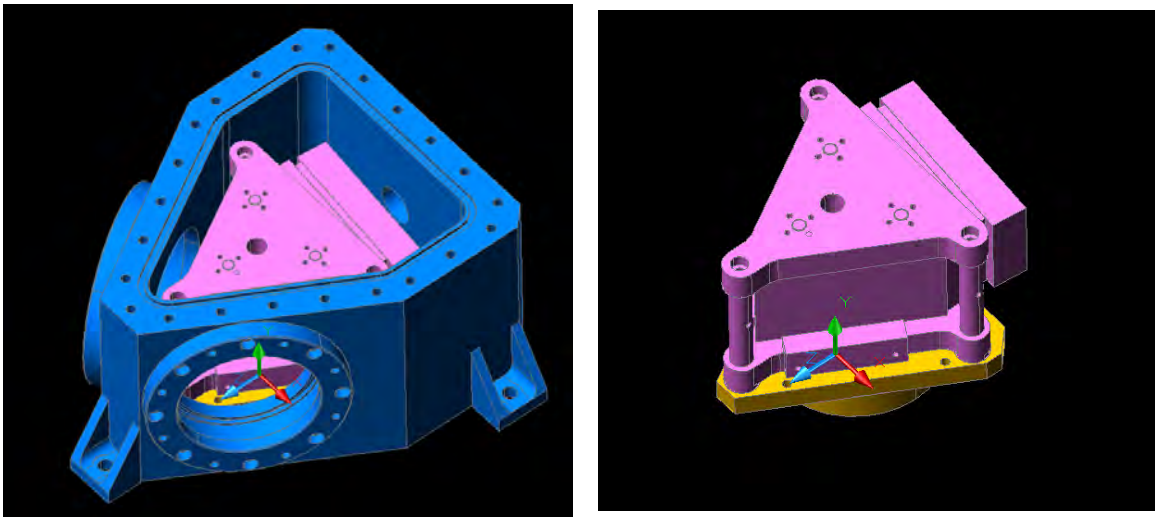


Figure 10: DASH interferometer enclosure

To minimize the thermal interaction between the ‘housing’, depicted in Figure 10 in blue and the interferometer shown in the same Figure as pink, the following was done;

- Bare, unpolished, machined Aluminum has an emissivity of about ~0.15-0.2
- Highly polished Aluminum has a much lower emissivity (0.05)
- The inside surface of the Housing was covered with first surface Aluminized Kapton tape
  - Tape with 966 Acrylic Adhesive was be used
    - Instrument is in a vacuum which will promote outgassing
    - 996 Adhesive has very low TML and CVCM, well below the NASA outgassing spec
  - 1 mil perforated tape was used
    - This helped to ensure no air bubbles were trapped beneath the tape when it was laid down
    - Air bubbles become blisters in the tape when exposed to a vacuum

3. ARROW INSTRUMENT HARDWARE

3.1 Interference Filter

A broadband interference filter is necessary in this instrument to prevent sampling spectral lines outside of the bandpass of the instrument which is from 628.019nm to 630.980nm. Barr Associates was approached to provide the following filter to both utilize the 630.480nm Neon

line (found in Ne penray lamps) which would be Doppler shifted and also to be potentially used from the ground with the O(^{1}D) 630.030nm atmospheric redline;

- Beam size: 33mm
- Cone angle (full angle): 8^o
- Passband shape: as 'top-hat' as possible
- Wavelength cut on: 628.7nm 0% to 629.8nm 100%
- Wavelength cut off: 630.48nm 100% to 630.69 0%

The cut on and cut off wavelengths were determined by referring to the atmospheric sky catalogue of atmospheric airglow emission lines developed by Osterbrock [Osterbrock 1996] and the emission lines available in Ne penray lamps manufactured by Oriel. This filter has been delivered within the delivery date forwarded from Barr Associates and is currently installed in the ARROW instrument.

3.2 CCD Detector Selection

A Princeton Instruments CCD model PIXIS 2048B was selected as the instrument's detector. Comparing price point, dark current performance, and readout noise on similar detectors between Andor, Princeton Instruments, and Hamamatsu the Princeton Instruments PIXIS 2048B detector was considered the best option.

One on the main performance factors considered was the readout rate of the CCD. Andor has a readout rate quoted at 33 kHz at a specified read noise. The Princeton Instruments detector readout speed is three times faster at 100 kHz achieving similar read noise specifications but reducing the accumulated dark current with a faster readout speed.

4. FABRICATION/ASSEMBLY

4.1 Custom Part Fabrication

Schematics of all mechanical parts requiring custom fabrication were sent out to three local machine shops for a request for quote. London Precision, Tidewater Machine Co., and Bechtel Plating & Manufacturing were contacted. The contract to complete all custom machining and fabrication aluminum parts for the ARROW instrument was awarded to the company New London Precision Instruments, located in MD as the y returned the lowest quote. A 30-day delivery time was deemed sufficient given the project schedule, number of parts, and the complexity of the parts to machine.

Alexandria Metal Finishers was selected to complete all anodization, as they are local and competitively priced.

4.2 ARROW Instrument Assembly

The custom fabricated parts were delivered by New London Precision Instruments on 2009.11.13, which was on schedule. Prior to anodization all parts were dry fitted to check designed clearances were meet. Several small changes to the instrument's design were fixed during the dry fit making this an extremely valuable exercise. Mid-way through the process of drying fitting, Figures 11 and 12 were taken.

All aluminum parts (except for the interferometer tank) were packaged and sent out for a flat-black anodization to Alexandria Metal Finishers-Industrial Plating and were shipped back to the Naval Research Laboratory on 2009.12.03.

Having all parts fit checked and anodization the final assembly of the ARROW was undertaken and completed on 2010.01.06, ahead of schedule. The fully assembled instrument is shown in Figures 13 and 14.

Figure 11: ARROW in the process of being dry fitted prior to anodization

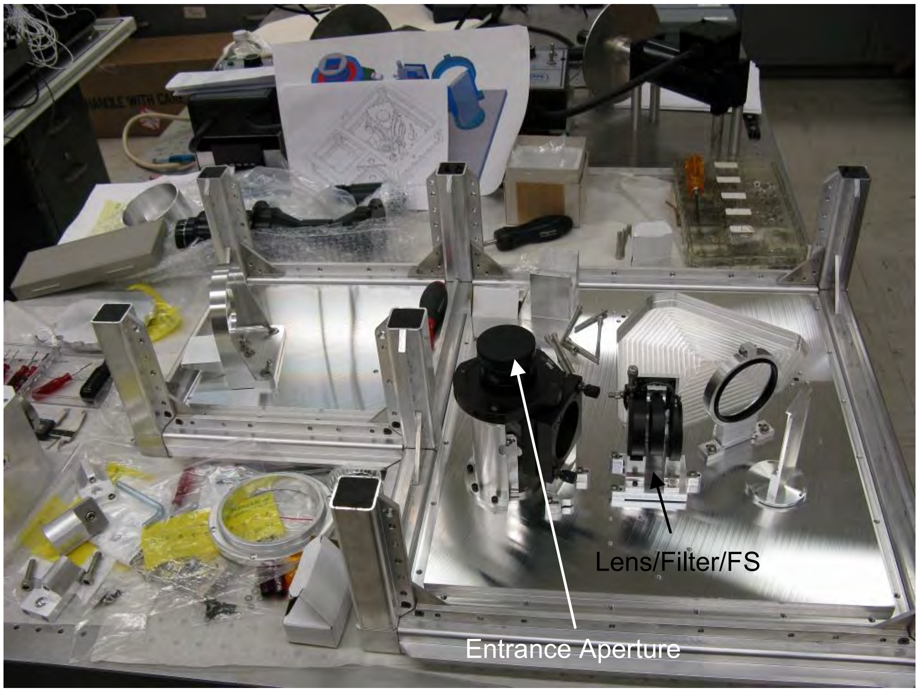


Figure 12: Another view of ARROW during dry fit

Note the structural frame in Figure 12 was only partially assembled to facilitate the installation of the components in the optical train.

Figure 13: Fully assembled ARROW instrument with light-tight covers on

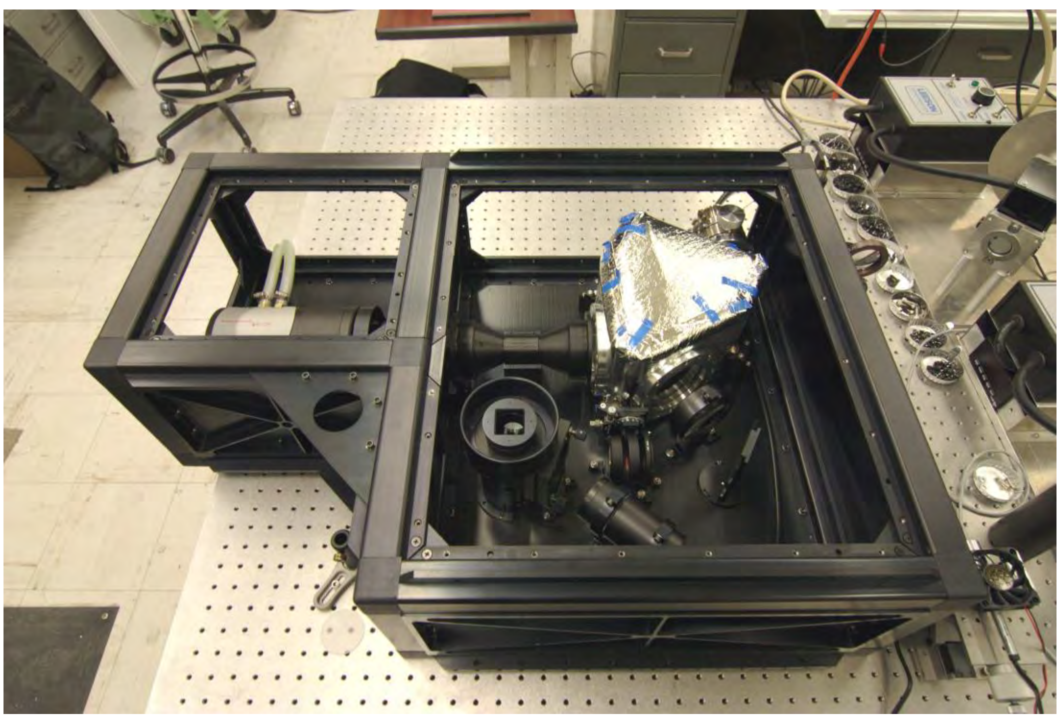


Figure 14: Fully assembled ARROW instrument with light-tight covers off

5. DOPPLER SCENE GENERATORS

One of the main ARROW project goals is to assess the performance of the instrument's wind retrieval accuracy by comparing what ARROW measures as a Doppler shift with what the actual Doppler shift is. Two scene generators, which can independently vary Doppler shifts of an incident emission line by a known amount, were assembled. The assembled scene generator is shown in Figure 16 with all parts listed in Table 2. Two generators were required to eventually simulate and test side by side FOVs on the CCD, which mimic a space flight scenario of a fore and aft FOV.

The maximum Doppler velocity the generators can produce is a function of the rotation rate of the retro-reflecting wheel Ω, the angle of the incidence beam to the wheel θ, and the distance from the center of the axle of the wheel to the incident beam *r*. The Doppler velocity *v*, is determined from $v = 2L\Omega$, where $L = 2\pi r\cos\theta$. In this specific case, *r*=10cm, θ = 45^{o}, and max. Ω is 3500 RPM. The maximum Doppler shift attainable with the current configuration is ±50ms^{-1}, which is sufficient to test the capabilities of the ARROW instrument as these velocities are within the typical wind speeds in the mesosphere and lower thermosphere.

The completed scene generator's optical and mechanical designs are shown below in Figure 15. A neon emission line was Doppler shifted to a known velocity and then directed into the FOV of the ARROW instrument.

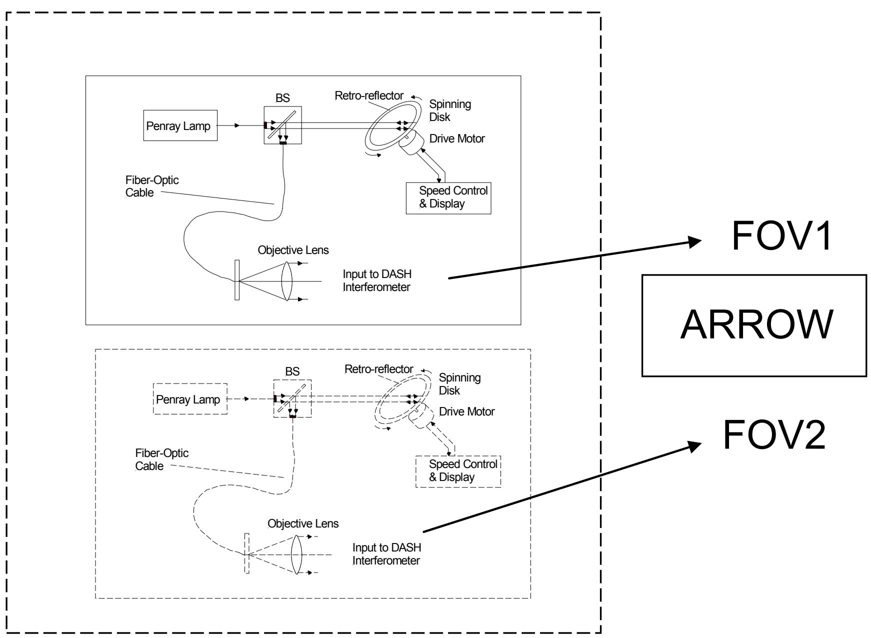


Figure 15: Schematic of the Doppler scene generator

Table 2: Parts list containing the principle components of the scene generator

Part Description	Part#	Company
Ne Cal Lamp (penray)	90-0015-01	UVP
Cal Lamp Power supply	99-0057-01	UVP
20 Degree Diffusing Angle 2"x2" Unmounted Sheet	NT55-852	Edmund
Beamsplitter	CM1-BS1	Thorlabs
Lens	n/a	Edmund
Scotchlite Reflective Material	8850	3M
Motor	M1120062.00	Leeson
Motor power/controller	174308	Leeson
rpm sensor (generator)	SB-757A-2	ServoTek
rpm readout display	DP5D0000	Red Lion
NEMA 4X/IP65 Plastic Enclosure for 2 PAX meters	ENC5C000	Red Lion

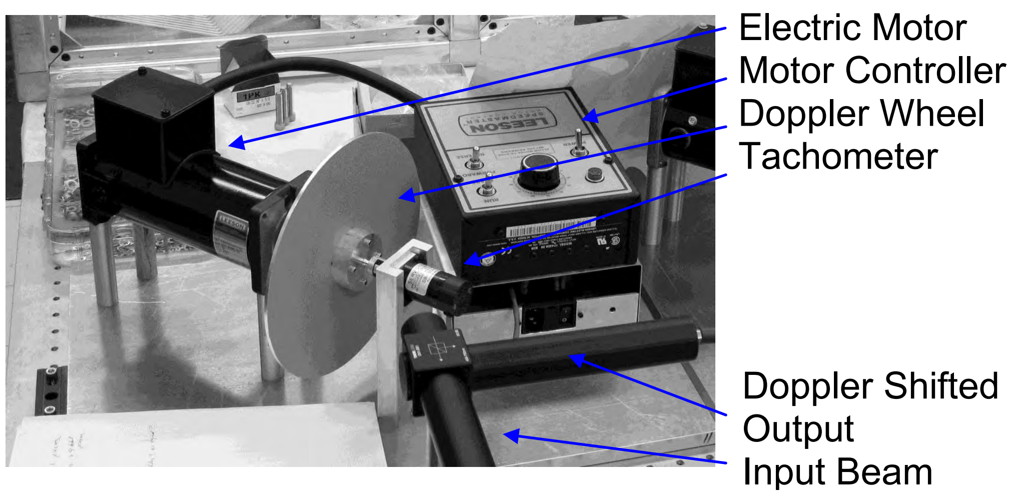


Figure 16: Assembled scene generator

6. WIND RETRIEVAL ALGORITHM DEVELOPMENT

Matlab and IDL software were developed during this SBIR Phase II to process the interferogram images acquired by the ARROW to retrieve Doppler winds. Examples of the considerations required during image processing are listed below. The software is available on request from the principle investigator.

6.1 Hot Pixel Correction Method

The identification of hot pixels becomes an important issue when using the classical phase unwrapping method of retrieving phases as a small number of hot pixels contained in a cross section of the interferogram (i.e. spectral dimension of the interferogram) can have a significant affect on the retrieved phase and subsequently the derived wind velocity.

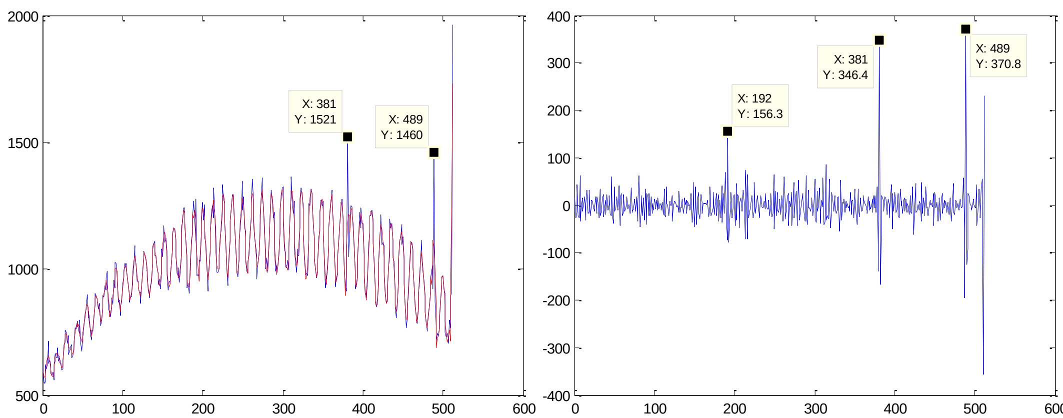


Figure 17: Example of a DASH interferogram corrected for 'hot' pixels within the row

Hot pixel identification becomes complicated as the interferograms have a lower polynomial structure in addition to a higher frequency cosine function along the spectral axis of the image which can be seen in left panel of Figure 17. In addition, along the spatial axis there is also slowly varying intensity values attributed to how the ARROW instrument FOV is filled from the input aperture. These two effects negate the possibility of setting a single scalar in looking for hot pixels.

An identification method for hot pixels was developed which used a Savitzky-Golay function to fit each row (i.e. the spectral dimension). The fit to the interferogram was subtracted from the original resulting in the right panel in Figure 17. Having a, now linear function, a scalar could be set to search for 'hot' pixels which required replacement.

The panel on the left in Figure 17 shows the original interferogram in blue with the fitted or ideal interferogram in red. The right panel shows the difference between the fitted and original interferogram of the left panel.
A raw image taken by the ARROW instrument from the Daytona field campaign is shown on the left in Figure 18 before 'hot' pixel correction, with the corrected image plotted on the right. In each image the three FOVs (Northward, Zenith, and Eastward) can be seen as distinct sections. See Section 8 for further detail on the three FOVs.

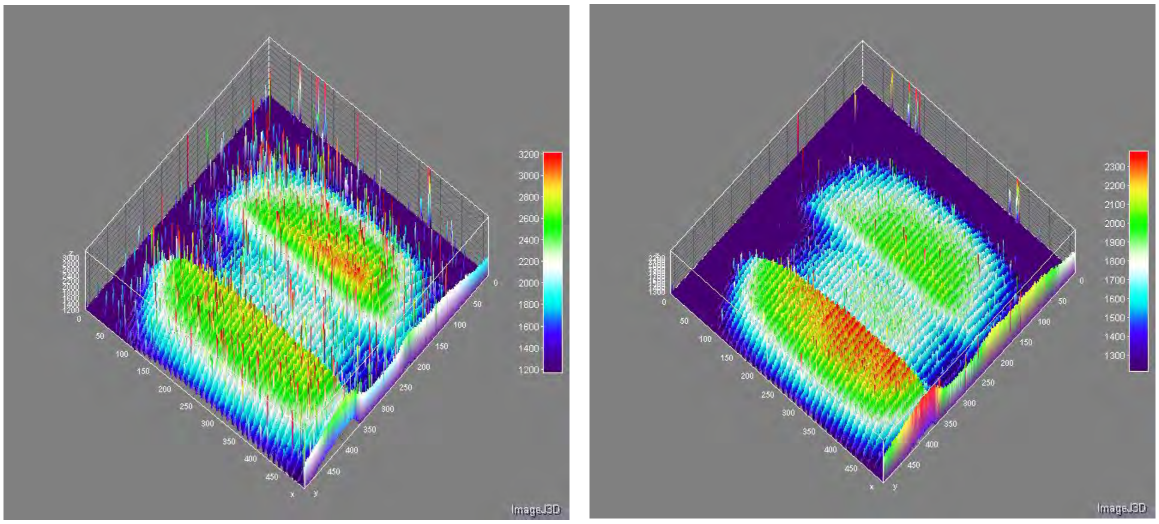


Figure 18: Hot pixel correction applied to a field campaign image taken by ARROW

6.2 Apodization Function Bias

It was also found in reviewing the Doppler wind retrieval algorithm that the apodization function which isolates the spectral feature in the FFT of the image prior to phase unwrapping could bias the amplitude of the phase shift. This bias is the result of convolving two non-Dirac delta functions which do not share an exact center peak. The solution to prevent the apodization function, which is a Hanning window, from biasing the retrieved phases was to use a modified boxcar function where the shoulders of the boxcar are replaced with Hanning function values.

7. LABORATORY DOPPLER MEASUREMENTS

Laboratory measurements of a Doppler shifted emission line, shifted by a known velocity, were successfully completed using a Doppler Asymmetric Spatial Heterodyne instrument for the first time. The Atmospheric Redline inteRferometer for dOppler Winds (ARROW) instrument, developed during this SBIR, retrieved wind velocities which were compared to the known imposed Doppler shift of a Neon 630.04nm emission line.

A Doppler shift was imposed on an emission using the Doppler scene generator shown in Figure 19. Focusing the 'input beam' from a Ne penray lamp onto a moving retroreflector (or the Doppler wheel in Figure 19) having an angle relative to the observer and with the ability to vary the speed of the rotating retroreflector allowed for a Doppler shift with a known velocity to be generated. The Doppler shifted beam returns from the Doppler wheel and is directed to the instrument using a beamsplitter, piped in through a fiber optic cable.

In Figure 20 the configuration in which ARROW was used is shown. The Doppler shifted line was piped into the instrument via a fiber optic cable mated to the calibration line lens assembly. The calibration line, which was an Argon backfilled Cerium hollow cathode lamp, was diffused and placed at the entrance aperture (orange line in Figure 20). This is opposite to the original use

of each port. As the intensity of the calibration lines, which consist of two Ce lines from the hollow cathode, were not intense enough to be piped into the calibration lens assembly and then reflected of the beamsampler at a 10% reflectance while maintaining short (<30s) integration times. The Doppler shifted Ne line however, was intense enough to be feed through the calibration lens assembly and reflected off the beamsampler into the interferometer and achieve an adequate S/N over relatively short detector integration times.

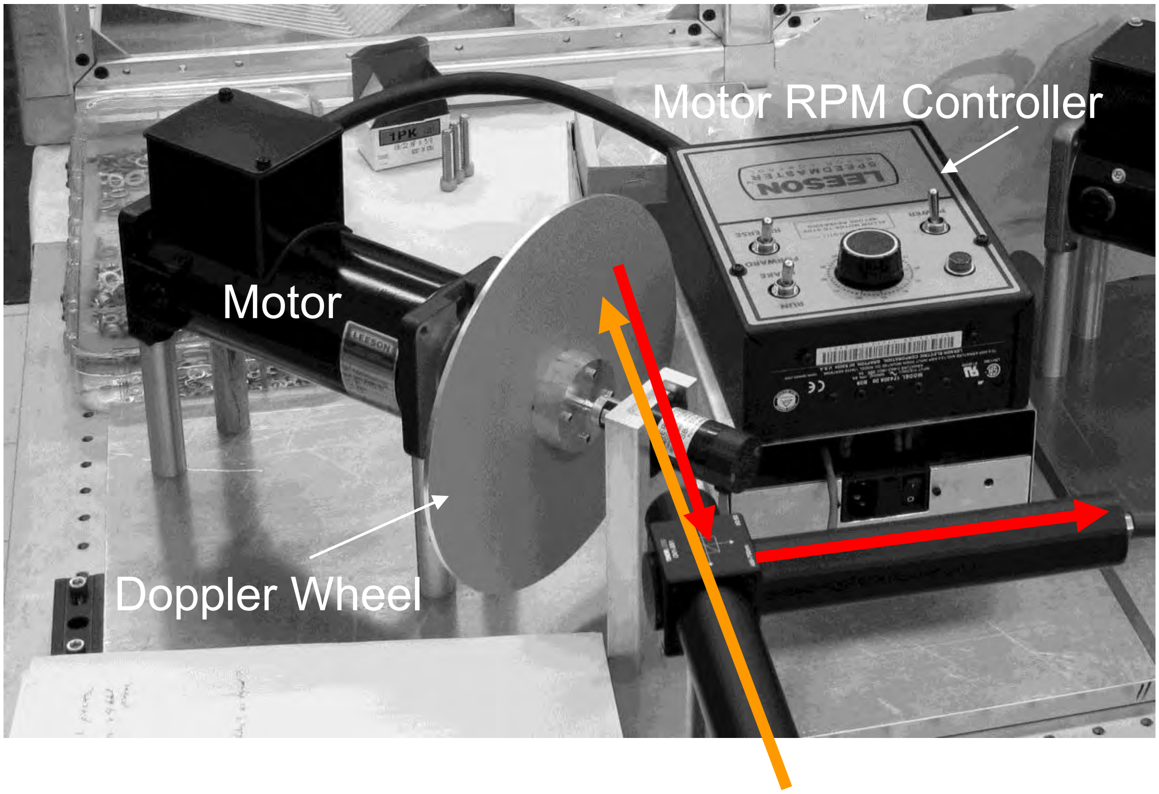


Figure 19: Doppler scene generator with simplified ray trace

In Figure 19 the non-Doppler shifted input beam from the Ne penray lamp is shown in orange. The Ne line is Doppler shifted (red arrow) after retro-reflecting off of the moving Doppler wheel and sent to the ARROW instrument via fiber optic cable.

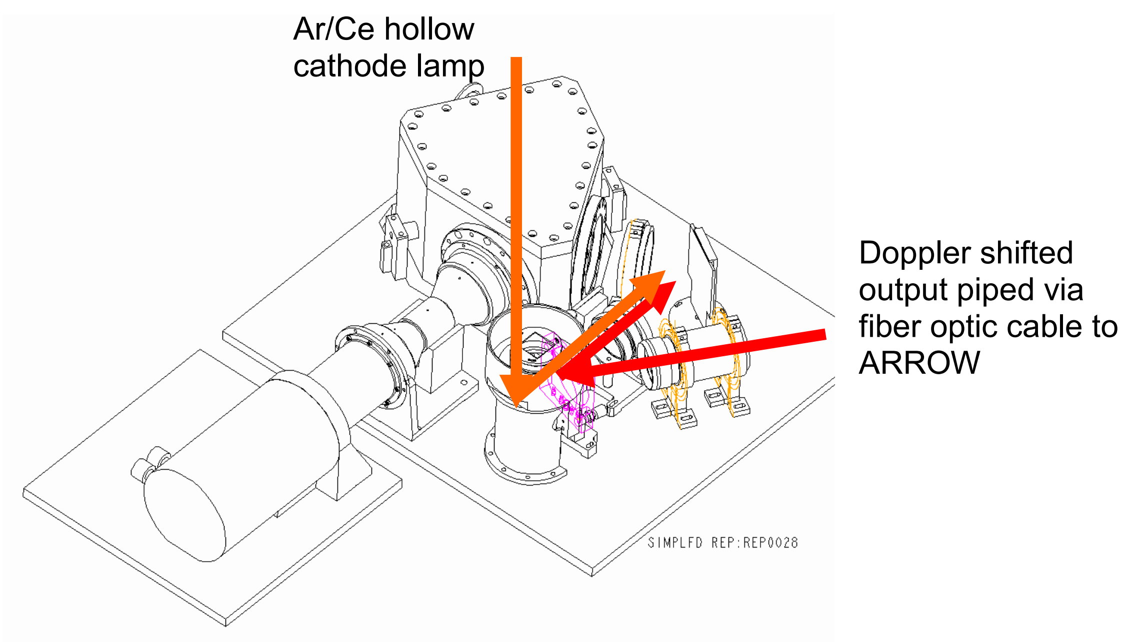


Figure 20: Simultaneous calibration line and Doppler line inputs

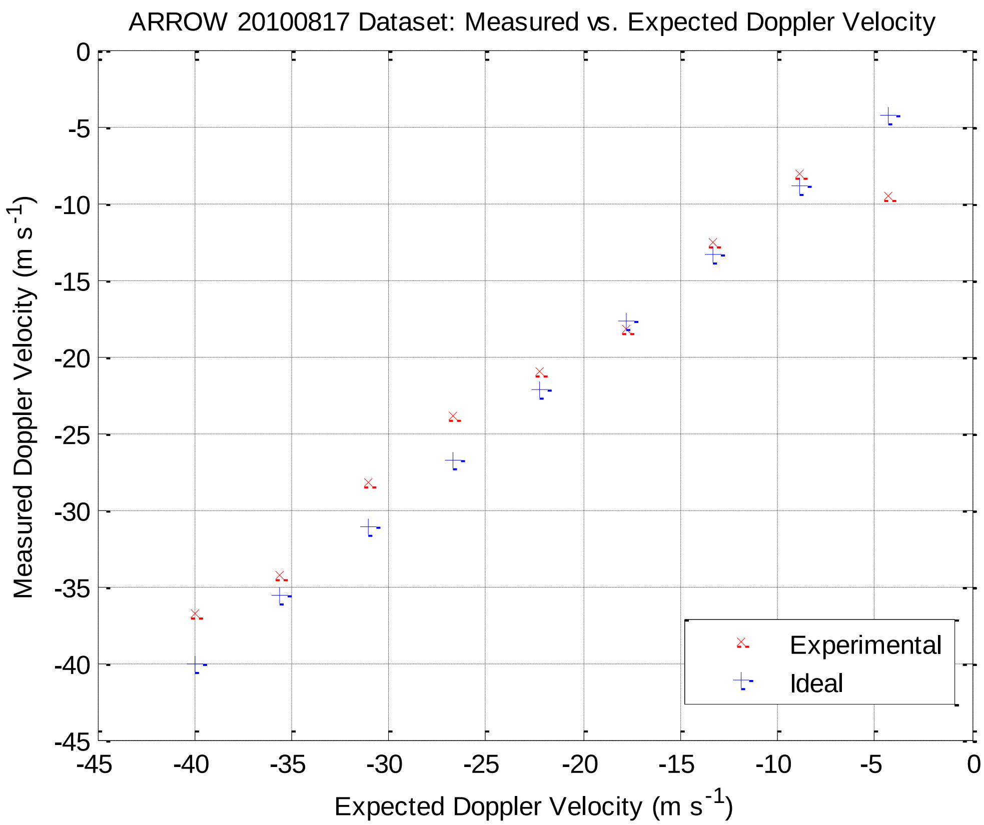


Figure 21: Retrieved Doppler measurements from the ARROW instrument

As the scene generator had full control over the imposed Doppler shift on the Ne line with a precision on the order of 1RPM of the Doppler wheel which corresponds to <<1ms^{-1}, the imposed Doppler shift was known to high accuracy.

Doppler measurements were made in steps of 5ms^{-1} from 0ms^{-1} to 40ms^{-1}. Measurements shown in Figure 21 are averages of 4 images at the same Doppler shift, zeroed to the last reference phase measurement, which was measured at the end of each Doppler velocity step. Integration times were 30s for each image with the complete trial taking 40mins. It should be noted that in reference to a DASH instrument observing the Earth's limb the required integration time would be much lower (estimated to be 3s from work completed in Phase I of this SBIR). The longer integration times of 30s were due to the throughput of the scene generator.

Preliminary comparison of the measured Doppler velocity to the expected Doppler velocity show excellent agreement. Although a full S/N and error source/impact investigation was not within the scope of this program the error bars are expected to be <±2 ms^{-1}.

8. ARROW FIELD CAMPAIGNS

8.1 Daytona Field Campaign

Having previously completed a preliminary set of Doppler measurements in the laboratory using the Doppler scene generator and the ARROW instrument, opportunities for a field test – although not a deliverable – were explored. Embry-Riddle Aeronautical University in Daytona Florida agreed to host the Atmospheric Redline inteRferometer for dOppler Winds instrument (ARROW) on-site in Daytona for a field test to last seven days. The motivation in field testing ARROW stemmed from the possibility of operating ARROW co-located with Embry-Riddle's Fabry-Perot, where both instruments would be measuring Doppler winds using the $O(^1D)$ airglow emission line at 6300Å. This would provide an actual geophysical dataset that could be directly compared with one another, albeit given different experimental error bars. The point of contact at Embry-Riddle is Dr. J. Hughes who agreed that ARROW would have in-kind support while in Daytona with the ideal outcome being a joint paper publishing the results in a peer reviewed journal with Dr. D.D. Babcock as lead author.

ARROW as designed and constructed for laboratory testing, did not have the capability to view multiple fields of view (FOV) as a ground-based instrument. To conduct a field test a separate 'observing turret' had to be optically and mechanically designed. The final design of the observing turret is shown in Fig. 22.

The observing turret has the ability to view two orthogonal FOVs with an additional part of the CCD detector dedicated to a zenith looking FOV. The turret also has the ability to rotate to different azimuthal positions but has the non-zenith FOVs fixed at 35^o elevation. The 35^o fixed elevation allows ARROW to take advantage of the van Rhijn airglow enhancement effect.

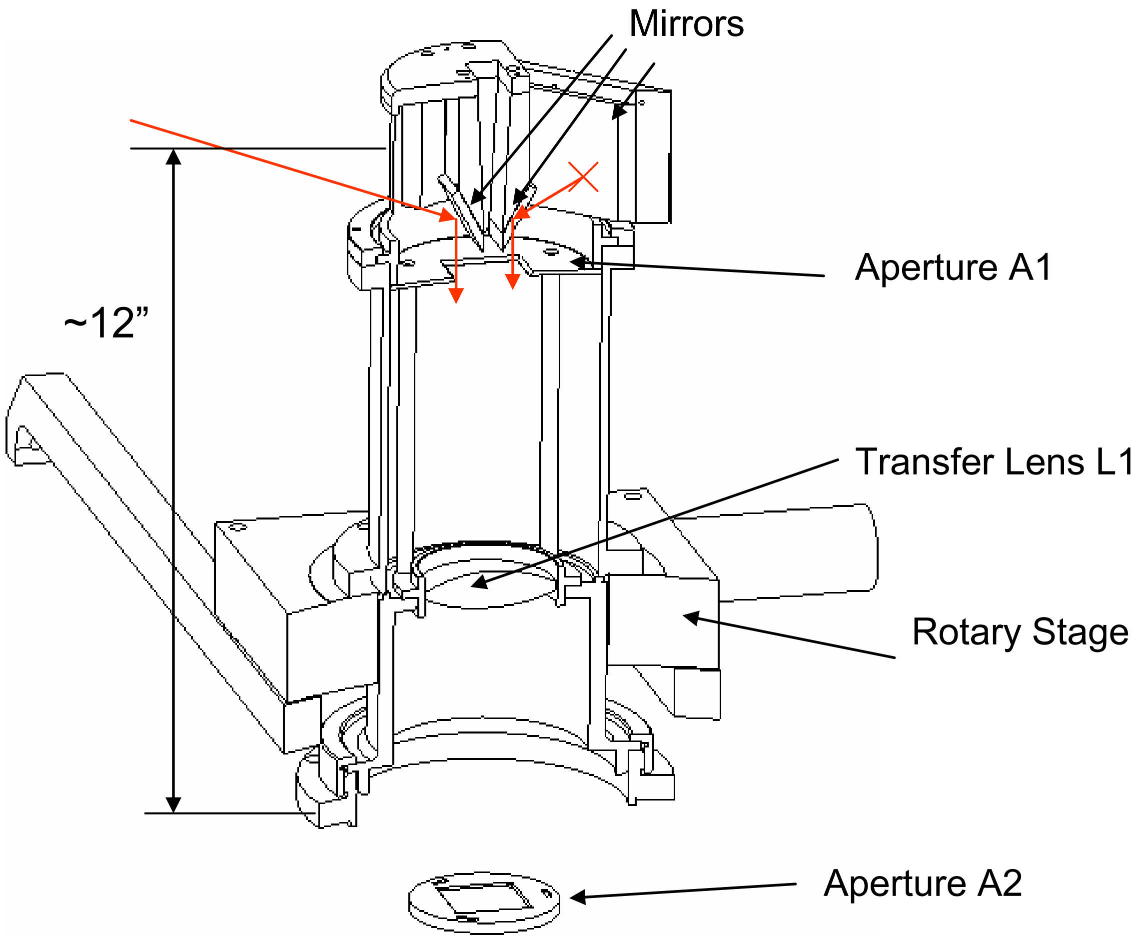


Figure 22: Schematic of the observation turret attachment

The observation turret in Figure 22 provides three simultaneous FOVs to ARROW - 2x orthogonal FOVs at 35^o elevation and 1x zenith. Aperture A1 is imaged on ARROW’s original instrument entrance aperture A2.

ARROW was shipped from Washington DC to the Embry-Riddle Aeronautical University on Nov. 7th 2010 and was operating – collecting images of the redline airglow – by Nov. 8th 2010. ARROW collected data from Nov. 8th 2010 to Nov. 12th 2010 where the observing conditions were favorable for the majority of the time. See Figure 23 for cloud cover conditions throughout the field test. It’s expected that only Nov. 12th 2010 had dense enough cloud cover to prevent the retrieval of Doppler winds; however, a successful wind retrieval will be dependant on the redline airglow intensity during the field test being sufficient enough to provide and adequate S/N, the Ne lamp calibration line intensity matching, and ARROW instrument temperature stability.

Analysis of the Daytona dataset is scheduled for next quarter. An example of the redline airglow as seen by ARROW is given in Figure 24. Pictures from the field test are provided in Figure 25.

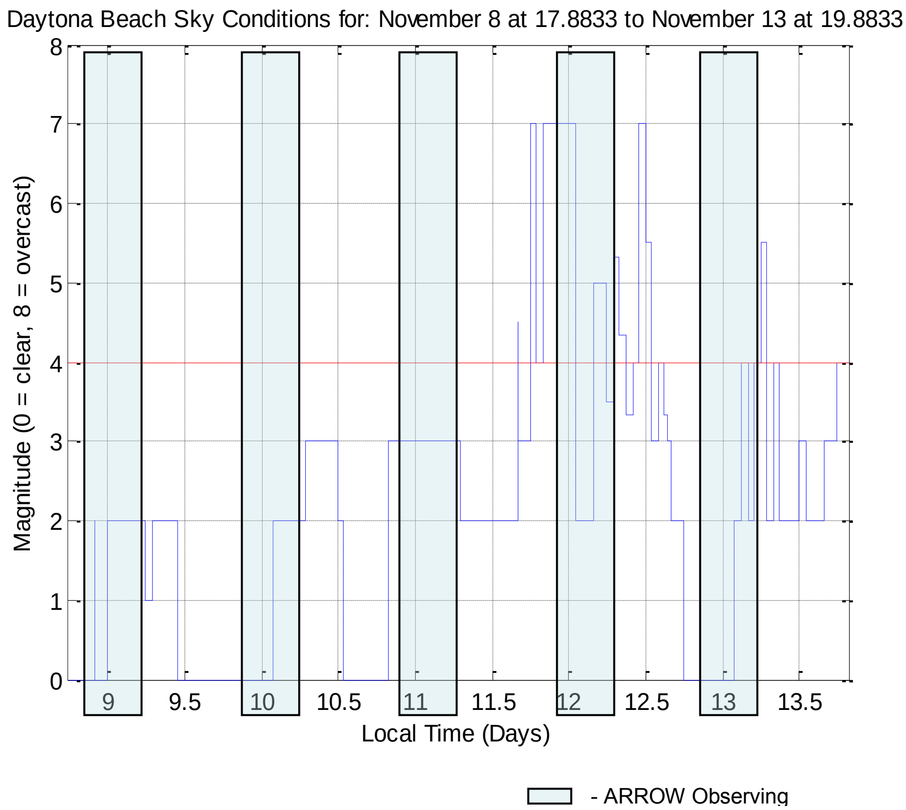


Figure 23: Cloud cover conditions over Daytona FL during the ARROW field campaign as reported by KDAB airport

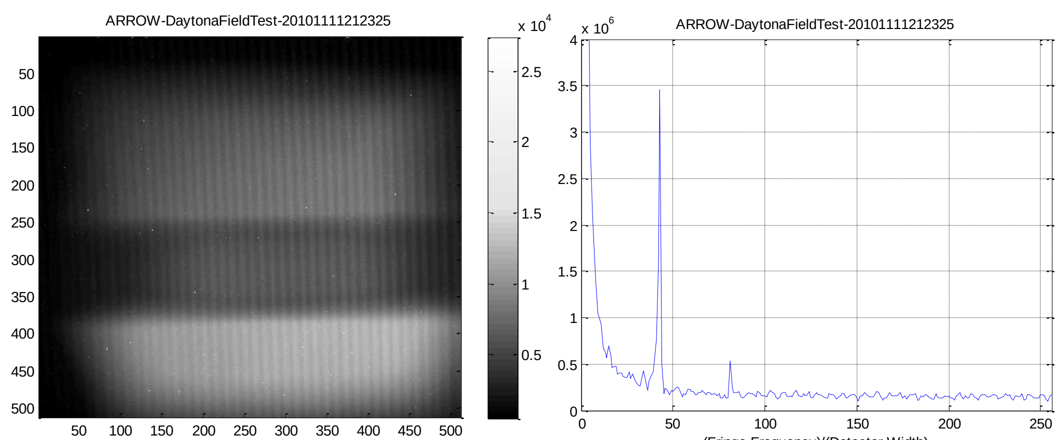


Figure 24: The redline airglow as observed from the Daytona field campaign

A raw image of the atmospheric redline taken by ARROW is shown in the left hand pane in Figure 24. On the right is the power spectrum showing both the Ne calibration line (43 fringes/detector width) and the $O(^1D)$ red line (81 fringes/detector width).

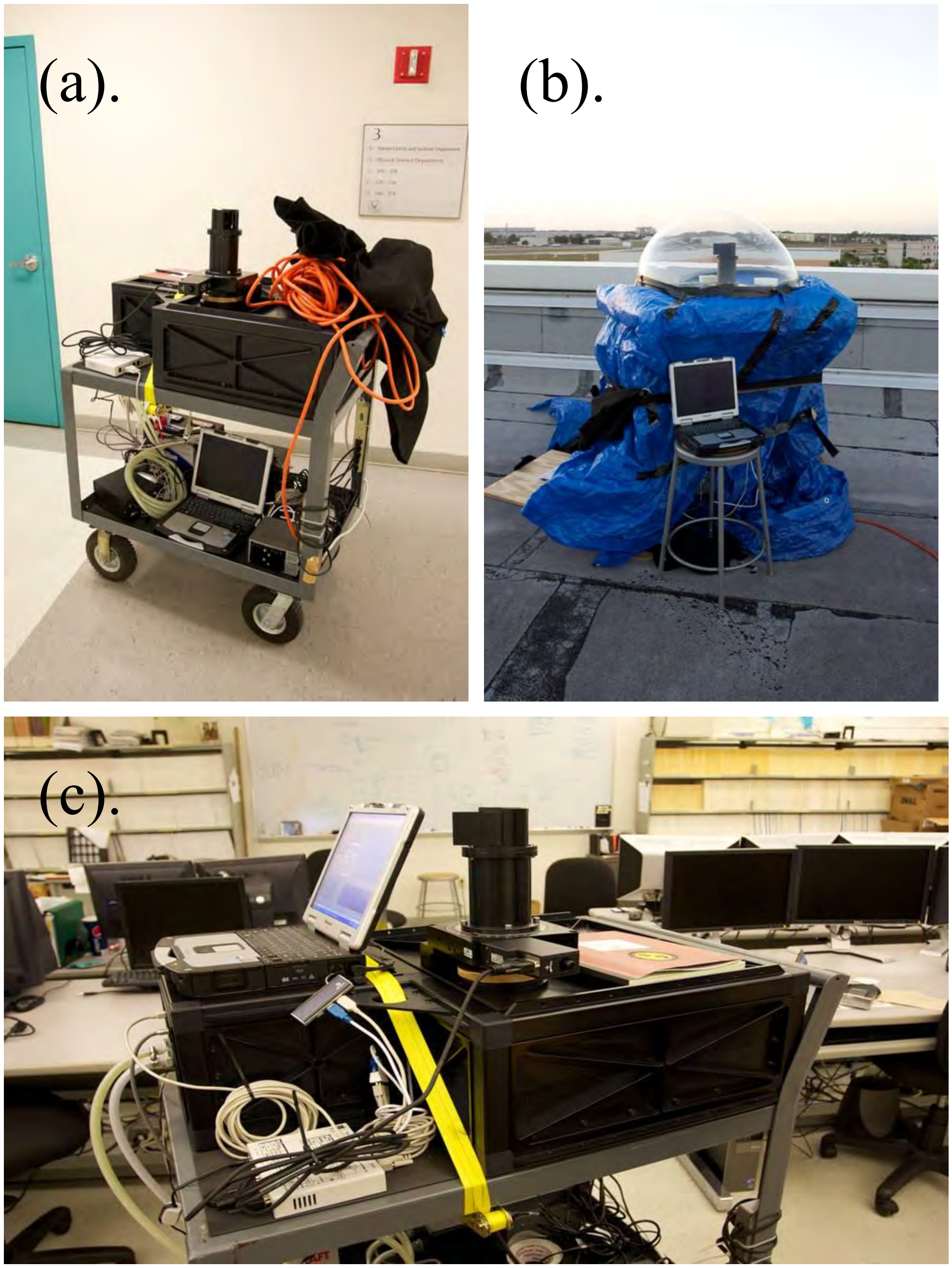


Figure 25: ARROW installed at Embry-Riddle Aeronautical University

Panel (a) in Figure 25 shows the full ARROW instrument with all supporting hardware configured to be portable via trolley. Panel (b) shows ARROW in operation with a vapor barrier installed to reduce condensation on the instrument optics during observations. Panel (c) is another view of ARROW in Daytona after being shipped from Washington DC and unpacked in Daytona.

The approach towards analyzing the data from the Daytona field campaign, where ARROW operated for close to a week at the Embry-Riddle Aeronautical University beside a Fabry-Perot measuring redline Doppler shifts, was to allow for a blind comparison of data retrievals between ARROW team members. This analysis was completed prior to seeing any F-P data from the Daytona group in an effort to have a consistent and agreed on dataset worthy of comparison. This was a thorough and deliberate process as this will be the first time that ARROW and the DASH optical technique will be compared to a co-located instrument with a long and successful operating heritage.

It is noteworthy that this effort differs substantially from the previous successfully retrieved laboratory Doppler wind measurement. Here in the case of retrieving geophysical winds, lower S/N, weather conditions (e.g.. clouds and aerosols), and challenging instrument environments where you have large operating temperature ranges, all contribute to the difficulty in Doppler wind retrievals.

The analysis of ARROW data obtained from the 2010 Daytona campaign has been completed for an observing night and sent to the Embry-Riddle Aeronautical University group headed by John Hughes. The Daytona group will compare the ARROW data with their co-located Fabry-Perot (FP) which was operating during the campaign. Both instruments were measuring the Doppler shift of the $O(^1D)$ airglow emission line at 630nm.

The Daytona campaign collected five nights of data from 2010.11.08 to 2010.11.12. This was the first field test for the ARROW instrument which was not originally planned for, nor a deliverable in the SBIR proposal; however, the decision to obtain a geophysical measurement with the ARROW instrument from the ground was made in an attempt to compare realistic thermospheric Doppler wind velocities directly with an established Fabry-Perot instrument. This comparison would potentially serve as a further demonstration that the DASH optical technique is a viable option to the aeronomy community for measuring upper atmospheric Doppler winds in addition to the laboratory demonstrations that have been successfully completed during this SBIR Phase II.

ARROW successfully obtained images of three FOVs simultaneously viewing the airglow from the $O(^1D)$ emission line generated by the thermosphere and an internal Ne calibration source. The North, Zenith, and Eastward directions were simultaneously imaged on the CCD with an integration time of ~30mins., which was required given the intensity of the red line during the campaign. After each integration period the observing turret, which controls the FOVs, was rotated to observe the opposite directions (e.g. South, Zenith, and Westward directions were imaged then North, Zenith, and Eastward, and then repeated).

The decision to conduct a field test was productive in that lessons were learned that would not have if ARROW had only been operated in a laboratory environment. The challenges involved retrieving Doppler winds from low S/N images, changing instrument temperatures, and image ‘hot’ pixel corrections which were much more prevalent given the long (30mins.) exposure times compared to laboratory test integration times.

The results from the observing night which started on 2010.11.11 are plotted in Figures 26 and 27. The date of the 2010.11.11 was chosen for analysis as it was the night which had the least amount of reported cloud cover. The plots convert Southward and Eastward winds which were measured, to their opposite directions of Northward and Westward for ease of comparison to other datasets. This conversion is why the cadence of the images in the Northward and Eastward directions appears to be 30mins., when the required time was 60mins. to cover the four cardinal directions.

Receiving feedback from the Daytona group will allow a comparison between the ARROW data and the measured Doppler winds from the Daytona group's FP, the agreement between the two datasets will be assessed and the remainder of the data analyzed. At the time of writing this report a comparison has not completed; however, this exercise is still seen as important and will be undertaken by the principle investigator after the Phase II is complete.

It should be noted that the analysis of the data taken on 2010.11.11 was the product and culmination of three independent analyses by ARROW team members that were compared, reviewed, and rerun to limit possible wind retrieval errors and ensure agreement on the processing algorithm. This was a long and deliberate process; however, it provided the ARROW team with a more thorough knowledge of the Doppler wind retrieval process and the sensitivities of the retrieval algorithm – something which had not previously been completed despite prior publications of results from DASH instruments.

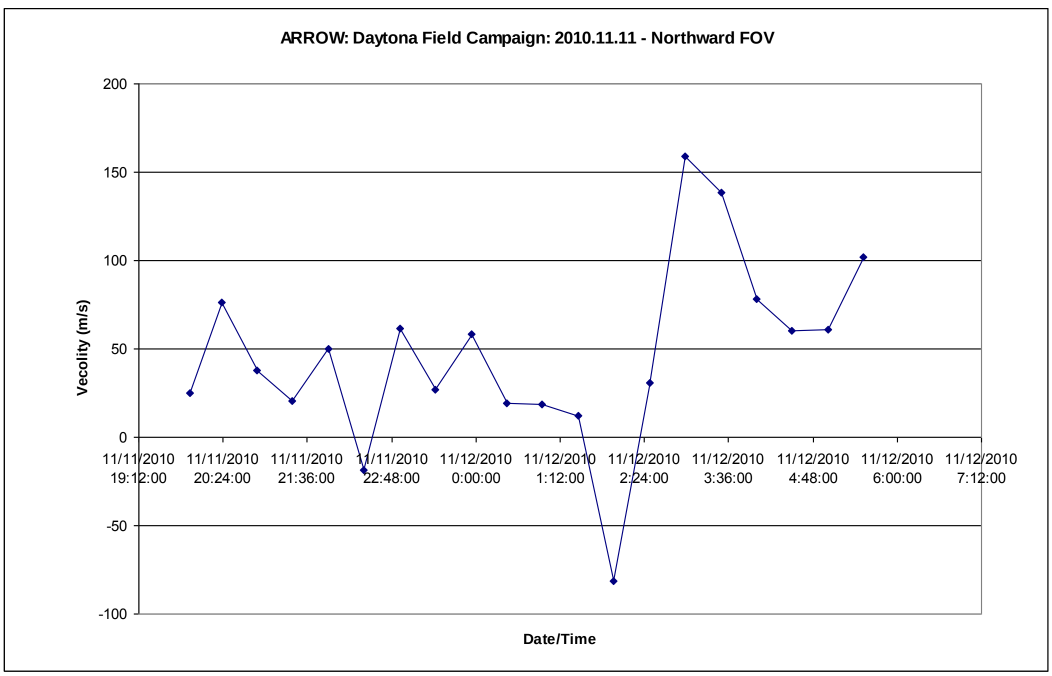


Figure 26: Northward Doppler wind component as measured by ARROW on 2010.11.11

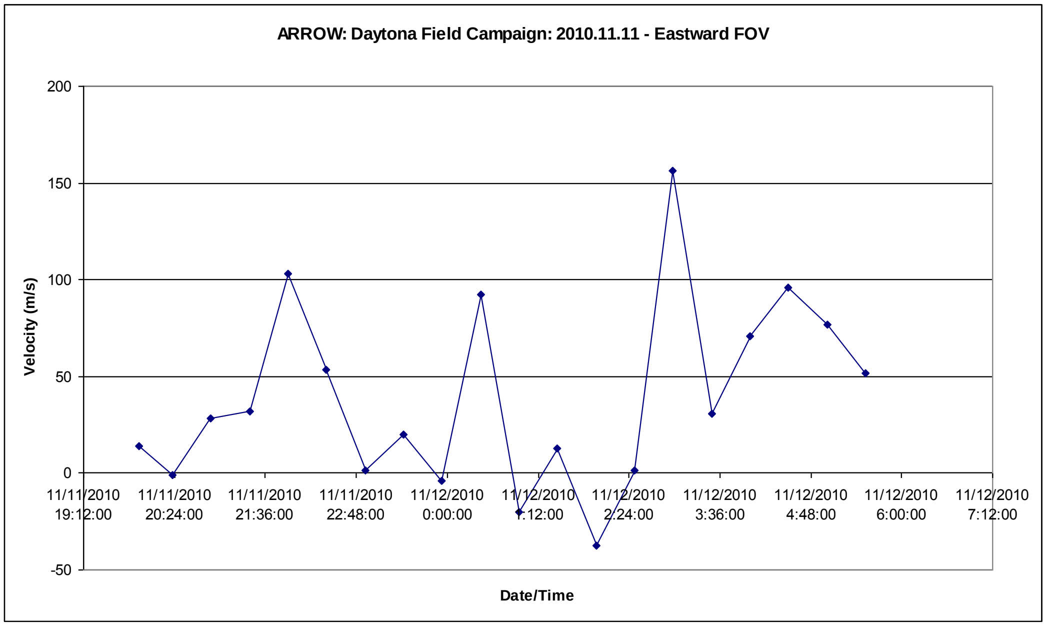


Figure 27: Eastward Doppler wind component as measured by ARROW on 2010.11.11

8.2 ALASKA FIELD CAMPAIGN

A second field campaign, this time in collaboration with Air Force Research Laboratory, was conducted at the High Frequency Active Auroral Research Program (HAARP) facility in Alaska. ARROW was shipped to Anchorage AK from the Naval Research Laboratory in Washington DC and was delivered, installed, and run at the HAARP facility by ARTEP Inc. personnel. The field campaign lasted from 2011.03.21 to 2011.05.12.

During the campaign there was a Fabry-Perot located at the HAARP site operated by Mark Conde's group from the University of Alaska Fairbanks. The data from this co-located F-P will be compared with ARROW's retrieved Doppler winds. The Alaska field test combined with the Daytona field test completed in 2010 will provide two independent datasets to serve as a validation of the ARROW instrument DASH optical technique and retrieval algorithms.

In preparation for the Alaskan field campaign ARROW had to upgrade the existing LabView code, which controls and collects data from the instrument's CCD camera in addition to controlling and timing the FOV rotation stage. This was completed and allows ARROW to run in a semi-autonomous mode where it initializes the CCD, automatically rotates the FOV at given intervals, and stores images in .FITS files along with instrument temperature data in the .FITS header. Although functional, this code is still considered to be in a beta version, since it was not intended to be developed with this high functionality.

Hardware upgrades were also completed before shipping to Alaska, including the option of using either a Ne penray lamp (which it was discovered are prone to high operating temperatures which significantly diminishes operating lifetime different from the penray lamp manufacturer

specifications) or a smaller Ne lamps. The commercially available NE-2 lamps were found to be two orders of magnitude cheaper with two orders of magnitude longer lifetime with the trade-off being lamp intensity. It was determined that the cheaper alternative would provide an adequate calibration Ne line intensity.

A second temperature sensor was placed inside the instrument on the Al mounting plate between the interferometer and the CCD detector. The purpose of this sensor is to record the internal temperature changes that could cause a potential change in the retrieved Doppler shift. Changes in internal temperature can cause the aluminum mounting plate to expand and contract moving the CCD focal plane relative to the interferometer. This movement would be recorded as a phase change of the fringes and therefore an erroneous Doppler shift. The calibration line should have the ability of negating any change in detector position; however, it was thought that as a diagnostic indicator, that the additional temperature sensor be added and recorded in each image file header.

In Figure 28 the ratio of the power spectrum intensities between the $O(^1D)$ red line and the Ne calibration lamp is plotted as a preliminary indicator of data quality throughout the campaign. This figure provides a starting point in gauging which observing nights to process for Doppler winds. (Note there exists data from the start of campaign which has been omitted from this figure).

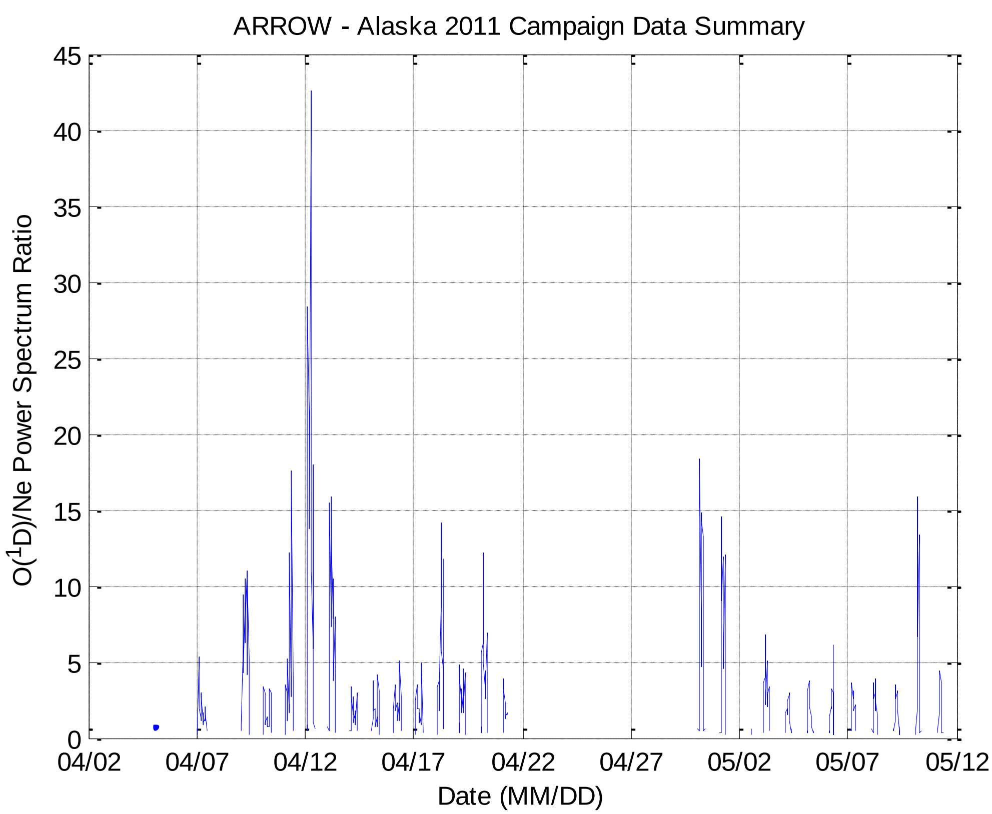


Figure 28: The ratio of the power spectrum intensities between the $O(^1D)$ red line and Ne calibration lamp

Again this field test was not planned for or part of a deliverable in the SBIR Phase II proposal but as with the Daytona field test, the opportunity to validate ARROW results with another Doppler wind instrument was seen as having a greater importance than continuing laboratory simulations of thermospheric winds – which had concluded successfully.

In Figure 28, there are a number of data gaps which were the result of software issues. ARROW's software had to be re-configured to run in a continuous observing mode – a mode which prior to the field test was not required. Overall the software performed well with the exception of last week in April where the software froze and Alaska personnel were not available to reboot the system.

The ratio of the power spectrum intensities between the $O(^1D)$ redline and the Ne calibration lamp provide not only an indication of where data exists but also provide an indication of the relative strength of the observed redline. The important point here is that there is a limit on where it is useful to have a stronger redline compared to the Ne calibration line. $O(^1D)$/Ne ratios greater than ~3 contribute an amount of multiplex noise which degrades the quality of the retrieved Doppler winds by >± 10m/s. Images or recorded interferograms where the $O(^1D)$/Ne ratio is ~2 should first be investigated as the multiplex noise contribution to retrieved winds should not be an issue.

Since the Alaska campaign, ARROW was successfully transported from the HAARP field site back to the Naval Research Laboratory in Washington DC. ARROW passed a return inspection and test of the internal optics upon arriving back at NRL; however the Phase II has been completed prior to obtaining the F-P dataset for comparison. As with the Daytona field campaign analysis, the Alaskan field campaign data comparison is seen as important and will be undertaken by the principle investigator post Phase II.

9. PROGRAM SUMMARY

To summarize the progress made over the duration of this program, the specific objectives that comprise the deliverables to AFRL from ARTEP Inc., as outlined in the SBIR Phase II proposal, are listed here with a summary of how those objectives were achieved. The sections referenced in this summary refer to sections in this report.

Specific Objective I: Develop a space flight prototype DASH instrument

Review Phase I conceptual optical design and determine optical tolerances

The conceptual optical design developed in Phase I of this SBIR was reviewed at the beginning of the Phase II. Changes were made to optical design to provide the ARROW instrument with the fore-optics which would allow the instrument to potentially be used from the ground to measure Doppler winds. See Section 2.1.

It should be noted that in the context of developing a space flight prototype instrument, that the fore-optics that were designed in Phase I would be a suitable design for flight; however, in Phase II it was deemed acceptable to design fore-

optics for a ground based instrument as they are not a technical risk which could affect the technical readiness level of the DASH optical technique. The change in optical design was discussed with and accepted by AFRL.

Status: COMPLETED

Identify a CCD detector with performance characteristics suitable to complete laboratory Doppler wind measurements

Multiple CCD vendors were compared as outlined in Section 3.2 and model PIXIS2048B CCD from the vendor Princeton Instruments was found to meet the criteria required to provide both laboratory and potential future ground based Doppler wind measurements of the redline airglow. The PIXIS2048B CCD was purchased, used for all testing and data images, and performed well throughout the program.

Status: COMPLETED

Complete custom design work for optical component mounting and instrument housing

A full instrument design, having gone through both a PDR and CDR, was completed using the CAD software ProE. COTS parts were integrated as much as possible to reduce cost and fabrication time. In many cases COTS parts were combined with custom components. Schematics of the instrument are shown in Section 4. All ProE files are available from the principle investigator.

As budget restricted the ability to design and fabricate a full space flight prototype instrument, the structure and housing used in Phase II differ from what would be used if designed as a satellite instrument detailed in Phase I. This was discussed with AFRL at the start of Phase II and found acceptable.

Status: COMPLETED

Develop a thermally stable vacuum interferometer enclosure

As the most critical component of the ARROW instrument was the DASH interferometer, a great deal of design and engineering work went into the interferometer enclosure. The enclosure which was built was successful in both maintaining an adequate vacuum and maintaining the thermal stability during laboratory testing and field campaigns.

The thermal engineering work put into the development of the interferometer enclosure and testing summary are outlined in Section 2.3.

Status: COMPLETED

Assemble, integrate, align, and test all components of the DASH flight prototype

The process of assembling, integrating, and testing all components was completed and it was determined that all components were functioning as designed and adequate to enable laboratory testing. Assembly Figures can be seen in Section 4.2.

Status: COMPLETED

A space flight prototype was designed and fabricated with the above considerations by ARTEP Inc. This hardware is available for AFRL to receive at the end of this program, as contrary to the SBIR Phase II proposal stating that all hardware was to remain at the Naval Research Laboratory in Washington DC. NRL has since agreed to handover all hardware including the interferometer to AFRL. This handover will be negotiated between AFRL and NRL.

Specific Objective II: Develop an optical Doppler shift scene simulator

Identification of a suitable monochromatic emission source to simulate an airglow emission and act as a calibration source

Two suitable emission sources were found with emission wavelengths that were both well spectrally isolated and with wavelengths close to that of the thermospheric redline airglow emission line. Ne penray (630.4798nm) lamps provided an extremely stable source to either use as a reference/calibration source and to Doppler shift. In addition to the penray lamps, hollow cathode Ar/Ce lamps were used. Two Ar lines (629.6872nm and 630.7657nm) from the hollow cathode lamp were used as reference/calibration lines throughout the program.

Status: COMPLETED

Develop hardware to simulate the scene of a Doppler shifted emission line of known wavelength shift

Scene generators were designed and built as detailed in Section 5. The scene generators were able to simulate Doppler shifts between $\pm 40 ms^{-1}$ controlled to known velocity within $\pm 0.005\ ms^{-1}$.

Status: COMPLETED

Optically design an interface to match the output of the scene generator to the two FOVs of the DASH instrument

As the FOV of the DASH instrument was changed from two FOVs, as in the design from Phase I to accommodate fore and aft FOVs which a satellite instrument would require, to one FOV or entrance aperture this interface was no longer required. What was incorporated into the ARROW instrument was the eventual ability to view two FOVs at right angles to one another, to facilitate ground campaign observing.

An interface was designed and built to match the output from the scene generator and input aperture or the one FOV of the ARROW instrument.

Status: COMPLETED

Specific Objective III: Measure the Doppler shift from a simulated scene of the Earth's Limb

Simultaneous FOV measurements of Doppler shifted images with known velocities which correspond to realistic $O(^1D)$ airglow emission intensities and wind speeds in the upper atmosphere from 100-300km

The ARROW instrument has successfully retrieved simulated Doppler winds similar to the speeds of the thermosphere using a more challenging emission source intensity than that of the average thermospheric red line airglow intensity. The intensity of the laboratory Doppler shifted Ne emission line was lower than what would be observed by a satellite instrument viewing Earth's limb and therefore a lower S/N, providing evidence that the performance of a comparable satellite based ARROW instrument would indeed be able to measure thermospheric wind velocities. The retrieved winds from a laboratory Doppler shifted emission source is detailed in Section 7.

From the work completed during this SBIR Phase I and Phase II by ARTEP Inc., AFRL now has a mechanical and optical design for a flight instrument where the mission critical component – the DASH interferometer – has been shown to capably retrieve Doppler winds.

The technical readiness level of DASH, due to the efforts of this SBIR, could be argued to have increased from the previous TRL level 4 to a TRL level 6, gained by operating a DASH interferometer under vacuum or in a space-like environment and having successfully retrieved Doppler winds.

Status: COMPLETED

Work completed in addition to the deliverables stated in the SBIR Phase II proposal

In addition to completing all deliverables as set out in Phase II, ARTEP Inc. developed and achieved the following all within budget;

- A rotatable 2 FOV observing turret hardware attachment for ARROW to provide the ability to measure thermospheric winds from the ground.

- LabView software to allow ARROW semi-autonomous operation for field campaigns controlling the observing turret position, the CCD camera integration time, wait time between exposures, and recorded image filenames.

- Completed a 7 day observing campaign at the Embry-Riddle Aeronautical University where a DASH instrument was operated beside a co-located Fabry-Perot also measuring Doppler shifts of thermospheric red line airglow.

- Completed a two month observing campaign at the HAARP facility. This was only the second time a DASH instrument has been operating with a co-located Fabry-Perot. Future comparison of the results is expected to occur after the finalization of the SBIR Phase II and it also expected that these results will be published in a peer reviewed journal.

- The efforts of ARTEP Inc. during both the Phase I and Phase II were presented to the scientific community, twice domestically at the Fall AGU Meetings in 2009 and 2010 and internationally during the COSPAR conference in Bremen Germany in 2010 and during the OSA FTS conference in Toronto, Canada in 2011.

REFERENCES

Englert C.R., Babcock, D.D., and Harlander, J.M., "Doppler Asymmetric Spatial Heterodyne Spectroscopy (DASH): Concept and Experimental Demonstration," Applied Optics IP, **46**, Issue 29, 2007, pp. 7297-7307.

Hays P., *et al*, "Remote Sensing of Mesospheric Winds with the High-Resolution Doppler Imager, Planetary and Space Science," Planet. Space Sci., **40**, Issue 12, 1992, pp. 1599-1606.

Killeen T., *et al*., "TIMED Doppler Interferometer: Overview and recent results," J. Geophys. Res., **111,** 2006.

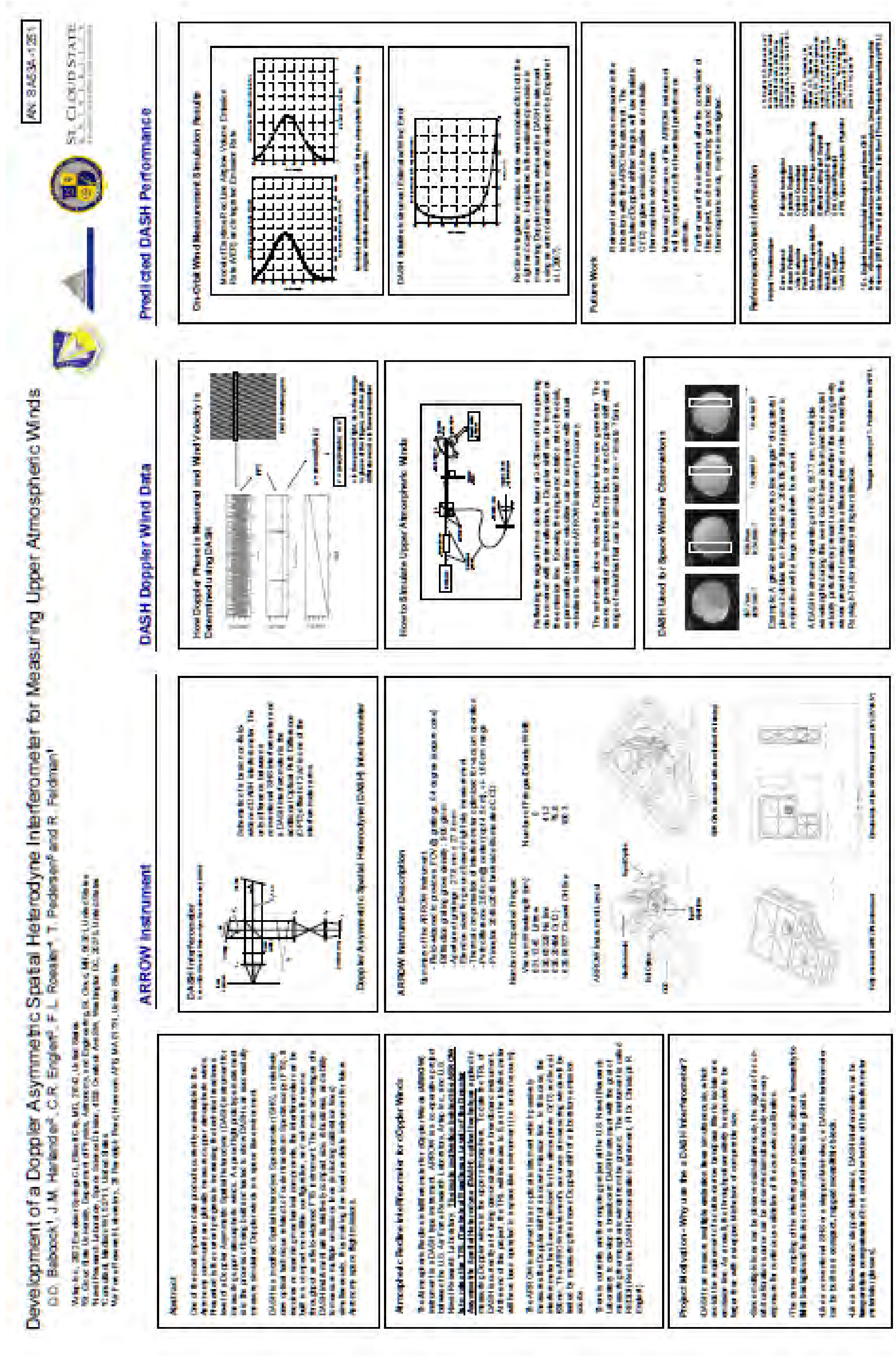
Meriwether J.W., "Studies of thermospheric dynamics with a Fabry-Perot interferometer network: A review," JASTP, **68**, 2006, pp. 1576-1589.

Osterbrock, *et al*., "Night-Sky High-Resolution Spectral Atlas of OH and O2 Emission Lines for Echelle Spectrograph Wavelength Calibration," Publications of the Astronomical Society of the Pacific, **108**, 1996, p. 277.

Shepherd G.G., *et al*., "Wind Imaging Interferometer for the Upper Atmosphere Research Satellite," J. Geophys. Res. **98**, 1993, pp. 10725-10750.

Roesler, F. L. and Harlander, J., "Spatial heterodyne spectroscopy - Interferometric performance at any wavelength without scanning," IN: Optical spectroscopic instrumentation and techniques for the 1990s - Applications in astronomy, chemistry, and physics; Proceedings of the Meeting, Las Cruces, NM, June 4-6, 1990 (A91-51460 22-35). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1990, pp. 234-243.

APPENDIX A – 2009 AGU Fall Meeting Poster



APPENDIX B – 2010 COSPAR Meeting Abstract

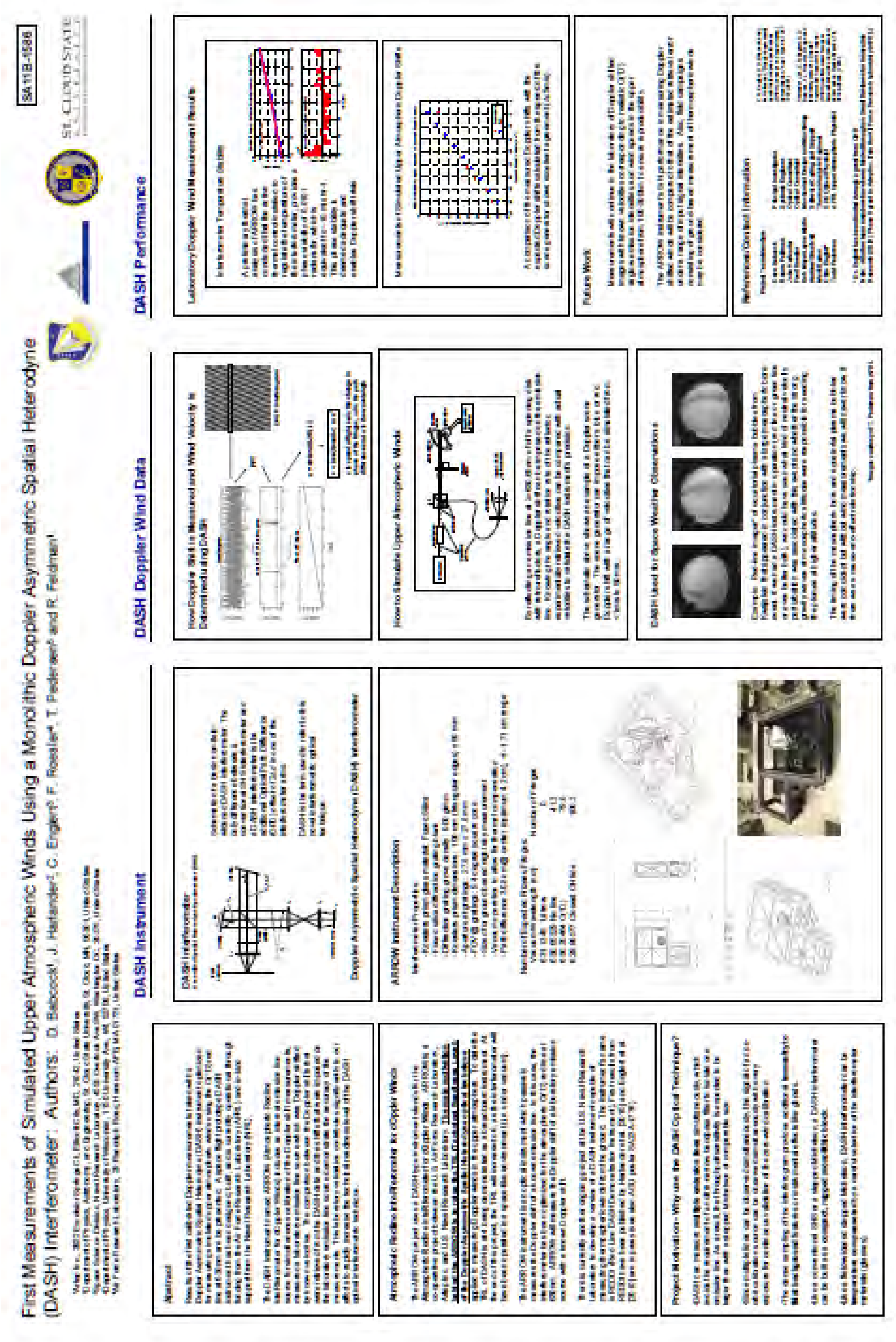
The principle investigator for this SBIR Phase II project attended the 2010 COSPAR meeting in Bremen, Germany from July 19th-25th. An oral presentation was given outlining the progress of the program to date including a review of Doppler Asymmetric Spatial Heterodyne operating theory, the schematics and design of the DASH flight concept with size, weight, and power numbers, a review of the laboratory instrument ARROW, and finally the thermal stability of the instrument. Abstract and title are included below.

> Title: Performance of a Space Flight Prototype Doppler Asymmetric Spatial Heterodyne (DASH) Instrument for Measuring Upper Atmospheric Winds
>
> Abstract: We will discuss the recent progress in increasing the technical readiness level of a space flight prototype Doppler Asymmetric Spatial Heterodyne (DASH) instrument for measuring upper atmospheric winds using the $O(^1D)$ red line at 630nm. DASH is a modified Spatial Heterodyne Spectrometer (SHS), and is therefore a close relative of a Fourier transform spectrometer (FTS) which can passively measure the Doppler shift of a known emission line. A DASH instrument has the ability to measure multiple emission lines simultaneously, which avoids the requirement of an ultra-narrow bandpass filter to isolate one emission line. As a result, the throughput/sensitivity is expected to be larger than with a stepped Michelson of comparable size. Since multiple lines can be observed simultaneously, the signal of an on-orbit calibration source can be observed simultaneously with every exposure for continuous zero-wind calibration.

During the presentation the investment and interest of the Air Force Research Laboratory in measuring upper atmospheric winds was stressed.

This talk is available on request to the PI.

APPENDIX C- 2010 Fall AGU Meeting Poster



Approved for public release; distribution is unlimited.

APPENDIX D – 2011 OSA FTS Meeting Abstract

An abstract was accepted to provide an oral presentation on the progress of the ARROW program to be presented at the Fourier Transform Spectroscopy (FTS) meeting of the Optical Society of America (OSA) in Toronto, ON Canada over July 10th to 14th 2011. The submitted three page summary has been cleared through NRL security and is provided below;

Doppler Asymmetric Spatial Heterodyne (DASH) Interferometer from Flight Concept to Field Campaign

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Abstract: We will review a flight concept for a DASH optical spectrometer to passively measure upper atmospheric Doppler winds, a completed laboratory DASH prototype instrument, and current field campaign results. **OCIS codes:** (010.0010) Atmospheric and oceanic optics; (010.0280) Remote sensing and sensors; (120.0280) Remote sensing and sensors; (120.6085) Space instrumentation; (280.4991) Passive remote sensing; (350.6090) Space optics; (300.6190) Spectrometers

1. Introduction

Doppler Asymmetric Spatial Heteordyne (DASH) interferometers are a recently developed optical technique [1,2]. DASH is characterized as a modified Spatial Heterodyne Spectrometer (SHS) [3], and is therefore a close relative of a Fourier transform spectrometer (FTS). DASH interferometers can passively measure the Doppler shift of a known emission line and when used to observe terrestrial upper-atmospheric airglow emissions provide line-of-sight velocities for the parcels of air containing the emission line. These observations are critical in developing a full understanding of the dynamics and energetics of the Earth's upper atmosphere; however, they are not currently available on a global coverage scale on a meteorological basis.

DASH interferometers have the ability to measure multiple emission lines simultaneously without sacrificing detector area, which avoids the requirement of an ultra-narrow bandpass filter to isolate one emission line. As a result, the throughput/sensitivity is expected to be larger than with a stepped Michelson of comparable size. A DASH interferometer can be built as a compact, rugged, monolithic optic that can be temperature compensated by a careful selection of the interferometer glasses.

A space flight prototype DASH instrument named ARROW for (Atmospheric Redline inteRferometer for dOppler Winds) has been designed, built, and is currently operational through funding from the Air Force Research Laboratory (AFRL) and in-kind support from the Naval Research Laboratory (NRL).

2. Flight Concept

Using the design of the WINDII michelson interferometer on UARS [4], being the most successful atmospheric Doppler wind instrument flown to date, an optical design with comparable etendue was developed for a space-based DASH interferometer as seen in Fig. 1. From a low earth orbit, a DASH instrument would measure thermospheric winds by measuring the Doppler shift of the redline O(^{1}D) 630nm airglow emission.

Since multiple lines can be observed simultaneously, the signal from an on-orbit calibration source can be observed simultaneously in addition to imaging the airglow emission line(s) for continuous validation of the zero-wind calibration.

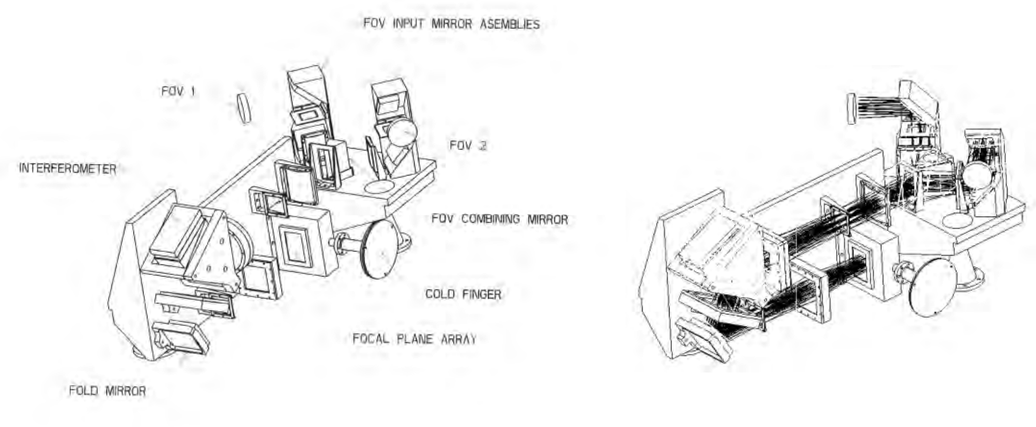

Figure D1. DASH flight concept schematic showing the main components of the optical train (left panel), in addition to a ZEMAX optical raytrace of the same DASH flight concept (right panel). Total physical dimensions when placed in an operational enclosure suitable for space flight are 28"l x 15"w x 12"h.

A conceptual optical and mechanical design have been completed in addition to the electrical hardware interface, estimated size, weight, power requirements, and estimated wind retrieval errors for a DASH flight instrument.

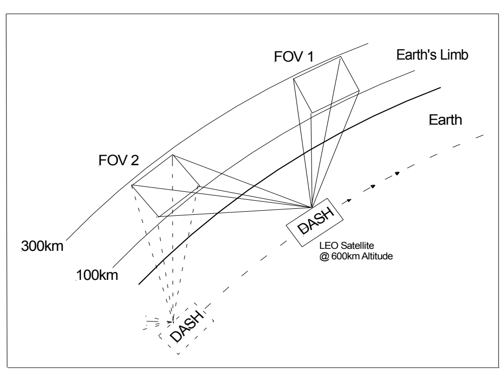

Figure D2. Typical limb viewing geometry for optical instruments measuring Doppler winds in the Earth's upper atmosphere.

A DASH flight instrument obtains a 2D wind vector by combining two 1D line-of-sight measurements. A DASH flight instrument measures the Doppler shift of a parcel of air first with the fore FOV and as the satellite orbits, the aft FOV soon views the same volume and measures the Doppler shift from a different perspective as shown in Fig. 2. As a Doppler measurement can only provide a 1D component of the velocity vector of the volume (an interferometer can only measure line of sight winds), the fore and aft measurements are combined to provide a 2D wind vector for that particular common volume of the upper atmosphere.

The scope of this current effort was not sufficient to produce a full flight prototype; however, it allowed for the construction of an laboratory prototype with an optical train similar to what would be used for a flight instrument outlined in the next section.

3. Lab Prototype

The ARROW laboratory prototype DASH instrument has been built and is currently operational. The ability of DASH to measure Doppler winds has been successfully tested by producing Doppler shifts of known velocities and comparing them to the Doppler shift mesaured by ARROW. These controlled laboratory tests have served to contribute significantly to our efforts to rapidly increase the technical readiness level of the DASH optical interferometric technique.

An effort is currently underway of using ARROW in field campaigns to measure upper atmospheric winds from the ground. The current status of this effort will be presented.

4. References

[1] Englert C.R., D.D. Babcock, and J.M. Harlander, “Doppler Asymmetric Spatial Heterodyne Spectroscopy (DASH): Concept and Experimental Demonstration,” Applied Optics, **46**(29), 7297-7307 (2007).

[2] Harlander J.M., C.R. Englert, D.D. Babcock, F.L. Roesler, “Design and laboratory tests of a Doppler Asymmetric Spatial Heterodyne (DASH) interferometer for upper atmospheric wind and temperature observations”, Optics Express, 18, 26430-26440 (2010).

[3] Harlander J.M., R.J. Reynolds, and F.L. Roesler, “Spatial heterodyne spectroscopy for the exploration of diffuse interstellar emission lines at far ultraviolet wavelengths”, Astrophys. J., vol. 396, no. 2, pp. 730–740 (1992).

[4] Shepherd G. G., G. Thuillier, W.A. Gault, B.H. Solheim, C. Hersom, J.M. Alunni, J.-F. Brun, S. Brune, P. Charlot, L.L Cogger, "WINDII, the wind imaging interferometer on the Upper Atmosphere Research Satellite", JGR, vol. 98, no. D6, pp. 10,725-10,750 (1993).

LIST OF ACRONYMS

AFRL	Air Force Research Laboratory
ARROW	Atmospheric Redline inteRferometer for dOppler Winds
CCD	Charged Couple Device
CDR	Critical Design Review
COTS	Commercial Off The Shelf
DASH	Doppler Asymmetric Spatial Heterodyne
FOV	Field Of View
FTS	Fourier Transform Spectroscopy
MLTI	Mesosphere Lower-Thermosphere Ionosphere
NCRADA	Navy Co-operative Research And Development Agreement
NRL	Naval Research Laboratory
OPD	Optical Path Difference
PDR	Preliminary Design Review
POC	Point of Contact
RPM	Revolutions Per Minute
SBIR	Small Business Innovation Research
SHS	Spatial Heterodyne Spectrometer
TIDI	TIMED Doppler Interferometer
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics
TPOC	Technical Point of Contact
TRL	Technical Readiness Level
UARS	Upper Atmospheric Research Satellite
WINDII	WIND Imaging Interferometer

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